Navigational Complexity Framework for EHR-Mediated Workflow in Perioperative Care

by

Benjamin Jacob Duncan

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Graduate Supervisory Committee:

Adela Grando, Co-Chair
Bradley Doebbeling, Co-Chair
David Kaufman
Robert Greenes

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ABSTRACT

Usability problems associated with electronic health records can adversely impact clinical workflow, leading to inefficiencies, error, and even clinician burnout. The work presented in this dissertation is concerned with understanding and improving clinical workflow. Towards that end, it is necessary to model physical and cognitive aspects of task performance in clinical settings. Task completion can be significantly impacted by the navigational efficiency of the electronic health record (EHR) interface. Workflow modeling of the EHR-mediated workflow could help identify, diagnose, and eliminate problems to reduce navigational complexity.

The research goal is to introduce and validate a new biomedical informatics methodological workflow analysis framework that combines expert-based and user-based techniques to guide effective EHR design and reduce navigational complexity. These techniques are combined into a modified walkthrough that aligns user goals and subgoals with estimated task completion time and characterization of cognitive demands. A two-phased validation of the framework is utilized. The first is applied to single EHR-mediated workflow tasks, medication reconciliation (MedRec), and medication administration records (MAR) to refine individual aspects of the framework. The second phase applied the framework to a pre/post EHR implementation comparative analysis of multiple workflows tasks. This validation provides evidence of the framework's applicability and feasibility across several sites, systems, and settings.

Analysis of the steps executed within the interfaces involved to complete the medication administration and medication reconciliation and patient order management

tasks have provided a basis for characterizing the complexities in EHR navigation. An implication of the work presented here is that small tractable changes in interface design may substantially improve EHR navigation, overall usability, and workflow. The navigational complexity framework enables scrutinizing the impact of different EHR interfaces on task performance and usability barriers across different sites, systems, and settings.

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LIST OF ABBREVIATIONS

HIE	Health Information Exchange
HCI	Human Computer Interaction
CE	Cognitive Engineering
EHR	Electronic Health Record
TURF	Task, User, Representation, Function
PreOp	Pre-Operative
RA	Representational Analysis
KLM	Keystroke Level Model
CW	Cognitive Walkthrough
MAR	Medication Administration Record
SD	Standard Deviation

1 INTRODUCTION TO DISSERTATION DOCUMENT

1.1 Background

A task typically contains a sequence of physical and mental activities completed by a person with an intention within a specific environment. When collection of tasks are arranged in a consecutive order, they form a workflow (1,2). These workflows can vary in their overall goals, types of tasks and sequence and the environment they are executed in. In the healthcare setting, a clinical workflow is the consecutive set of care-related tasks that are completed during patient management (2). To understand complexities associated with clinical workflow, workflow modeling can be applied to explore the details of individual tasks. This includes physical, coordination, computational and cognitive tasks that clinicians perform during routine patient care. The depiction of work in the clinical setting aims to maximize clinical workflow while minimizing clinician burden (3).

Cognitive engineering (CE) can be applied to create interfaces that support practitioners workflow in a specific domain (4). CE achieves this through an interdisciplinary approach, developing methods and tools to assess and guide system design. User resource such as specialized knowledge, information type management and the use of various tools and artifacts within a system can be assessed through CE, leading to design changes. Because of the known complexity of clinical workflow and associated systems, a more systematic approach to evaluations is necessary.

In the healthcare setting, EHR users divide their cognitive efforts between navigating a system's interface and executing a workflow task (5). EHR navigation can also contribute to complications with clinician decision-making processes involving access and organization of information, creating challenges to completing work (6,7). To achieve a more streamlined EHR-mediated workflow, bottlenecks within system design that impede task performance should be identified.

EHRs have the intention of streamlining clinical workflow, resulting in improvement in quality of patient care and clinician user experience. EHRs have become a vital tool for clinicians to document patient information, aid in clinical decision making, and access knowledge and information (8). There are continuous efforts to ensure efficient utilization of EHRs because of their impacts on healthcare quality indicators, such as documentation quality, efficiency, and guideline compliance (9). However, while there have been improvements to the delivery of care, the quality of EHR design remains the same. Numerous reports show clinicians remain dissatisfied with EHRs, stating systems do not support their cognitive workflow and information needs (10,11).

While EHRs can be a valuable tool for accessing and documenting patient information, studies have found that they are also a new contributing factor to clinician stress and burnout (12). The unintended consequences of EHRs, such as poor software design and workflow integration, create excessive cognitive load through inordinate documentation requirements. These unintended consequences of poor EHR design and integration are a significant contributor to clinician dissatisfaction and, in turn, burnout (12–14). It has been found that an increase in clerical burden required by clinicians is associated with burnout. Micek et Al. found that burnout was directly related to the amount of EHR use during patient care sessions (15).

A point of concern raised during EHR implementation and use is the system's usability: the extent to which the system can be used efficiently and to the clinician's satisfaction (16,17), and its effect on patient care. Poor usability of EHRs may introduce patient safety risks that could potentially lead to clinician frustration (17,18). With the widespread implementation of EHRs, documentation burden is also a new challenge. With the implementation of health IT requiring complex navigation and documentation, clinicians spend up to two hours on an EHR for everyone hour spent interacting with a patient and up to two hours outside working hours completing EHR-related tasks. While documentation burden can be cited as a primary contributor to increased EHR use, poor usability and design contribute to clinician dissatisfaction (15,19–21).

Increased EHR use also creates patient safety concerns that can be contributed to poor system usability. Patient safety concerns are adverse events or unsafe conditions that increase the likelihood of a safety event occurring (22–24). There is a lack of current data streams used to identify the nature of these patient safety concerns. There have been found to have EHR-related patient safety concerns regarding the use of system-system interfaces and hidden dependencies within documentation (22,25). One of the important components to minimizing patient safety concerns is the implementation of standard interface design guidelines and functionalities (22,25). These guidelines are an essential foundation for user-centered design while minimizing patient safety concerns.

User-centered design is not often considered in EHR construction by software designers, resulting in inconsistent design, poor readability and navigation, and substantial variation across different interfaces. Providers often perceive EHRs as difficult to use, and usability analysts have cited issues with difficult-to-read interfaces, confusing displays, and iconography lacking consistency (26). The design and development of surgical-specific information systems often raise a variety of challenges for designers. The main issue is that an abundance of patient information is available through the narrow lens afforded by a computer display. This problem is known to represent a significant EHR usability bottleneck (27).

The healthcare domain especially has demonstrated that careful attention needs to be paid to actual work practice. Otherwise, mismatches may appear between a tool's workflow assumptions and how the tool works in reality (4,28,29). To understand users' work strategies and system interactions, the co-dependency between the two must be detailed. Systems have constraints built into their design, facilitating a series of interactive behaviors by the user. The user must comply with these constraints and use microstrategies, a sequence or pattern of interactive behaviors (30), to navigate these constraints and complete their task. The constraints required by the system usually do not consider the complexity of the work domain and require the user to employ tradeoffs of working memory, perceptual-motor actions, and visual search, complicating the microstrategies to complete the task (17,31). Working memory is the ability to hold information temporarily when completing a task, perceptual-motor actions are physical actions when interacting with a system and visual search is the scanning of a digital environment for a piece of information.

Working memory, perceptual-motor actions, and visual search provide a means of characterizing the cognitive complexities of task performance in a system design. While the CE approach should be considered in design, there is also a need to evaluate existing systems to improve usability. Those evaluating systems, especially the implementation of HIT, are responsible for questioning the safety implications of system usability (32). During the design and development phases, integrated evaluation methods are needed to ensure the system functions to aid users and to ensure the system is appropriate for the work domain. There are existing frameworks that assist in the identification and use of evaluation methods for HIT.

The task, user, representation, and function (TURF) EHR usability framework aims to describe, explain, and predict usability differences by drawing on objective, quantifiable measures (33). While these frameworks evaluate EHR usability and assess the effectiveness of evaluation methods, there is a lack of connection between static usability evaluations and workflow. Extensive usability testing and EHR-mediated workflow modeling may help address inefficient EHR design, reduce documentation burden, and explain how interfaces create complexities in EHR navigation (34,35). It is a measurable construct that reflects the degree of difficulty in executing the steps in an EHR task.

EHR-based navigation is a primary aspect of system use. This can be defined as "desktop-based interaction with user interface presentation and controls that allow users to locate and access needed information" (36,37). Navigation is the path taken to complete a task, including the actions (e.g., mouse clicks) and the traversal through space (e.g., negotiating a sequence of screens). EHRs may require users to navigate through interfaces, seeking data to create an adequate mental model of a patient case. Two main types of navigation exist: between page and within-page (36,37). The difficulties users face with the interactions required to navigate through the interface, referred to as navigational complexity, can create unnecessary cognitive load (37). Problematic EHR navigation, such as switching between interfaces or searching for patient information, can generate usability bottlenecks and user frustration.

Navigational complexity is often impacted by unintuitive and tedious interface. Increases in navigational complexity require more resources to be devoted to interacting with the system and less to thoughtful task completion. Often, interface design elements can create unnecessary complexities when navigating the system. The study of navigational complexity is a bridge between static usability evaluations and workflow. The term "complexity" has a wide range of meanings in informatics and more broadly in scientific research (38). In this context, navigational complexity is a narrowly construed measurable construct that reflects the degree of difficulty in executing the steps in an EHR task. If navigational complexity can be minimized, this can provide significant ease of use to clinicians without redesigning an entire interface. Because of ease of modifying navigation, it should be a primary area of focus for improvement.

Traditionally, single method approaches, user-based and expert-based, have been used for analyzing navigational complexity (39–42). User-based methods involve analyzing real-world scenarios of clinicians interacting with an EHR to determine constraints users face. Expert-based methods analytic are completed by usability experts to model processes required to complete a task. By employing these two methods in concert, a more comprehensive picture of navigational complexity is possible.

The research goal is to develop and validate a new biomedical informatics methodological approach that combines expert-based and user-based techniques to guide more effective EHR design, improve usability, and reduce navigational complexity. The proposed methodology and its practical value are demonstrated when applying it to the study of EHR-mediated workflow completed by nurses in the pre-operative (PreOp) setting. After an initial literature review, advantages, and disadvantages of single user-based and expert-based methods for analysis and identifying bottlenecks are presented versus a combination of methods. A variety of user-based and expert-based methods is then proposed to differentiate the performance of user interfaces across systems, users, and tasks.

A two-phased validation of the framework is utilized: a single, EHR-mediated workflow task and a pre- and post-implementation comparative analysis of multiple systems. The first phase of validation is small-scale to confirm that the selected methods are able to identify all bottlenecks in the workflow with a single task. This validation allows for fine-tuning of the framework. Once the combination of methods is confirmed, the second phase of validation applies the framework pre- and post-implementation of an EHR to determine differences in performance between the two systems. The second application phase of the framework validates that the framework can be applied across multiple systems, sites, settings, and tasks, and that the execution of the framework is streamlined.

Data collection and framework validation was completed during the PreOp nursing patient checkin process. PreOp workflow was selected because the workflow is relatively routine and constant per patient case. With the cost associated with surgery in the healthcare setting, it is important to have an in-depth understanding of the PreOp care process. This environment also requires a heavy documentation workload, leading to frequent use of the EHR in the PreOp department. Additionally, nurses are the primary care providers that interact with the EHR, so characterizing EHR use for this role can provide a deeper understanding of the overall PreOp workflow. Evaluation and validation are completed on in-situ observational data in the PreOp setting versus in the lab environment. This enables the scrutinization of interactive behaviors, identification of interface elements and other factors that contribute to task complexity.

This scrutinization of interface elements and system navigation can be generalized to any number of clinical settings, tasks, or individual processes. The framework is structured in a way that it acts as a data collection and analysis handbook for anyone aiming to assess interface navigation. The frameworks detail the resources, steps and results for data collection and analysis, regardless of IT system or clinical setting. The main goal is consistency across the area of focus: to model and propose changes to EHR-mediated workflow. The data collection process describes pre-data processing and resources that are required of any organization and details regarding the type and quality of data necessary for analysis. In terms of data analysis, the framework describes the various data streams generated and how they can be leveraged regardless of existing interface design. A stepwise process of how to complete data analysis is provided as well to allow for any analyst, regardless of experience or knowledge level, to complete the analysis. Because the framework is based on identifying and focusing on the modes of interaction within a system rather than the category of information being documented, it can be applied to any navigation path, regardless of site, system, or clinical setting.

The framework leverages a combination of qualitative and quantitative data that provides high reproducibility while using a microanalytic approach to observe small changes in the interface and their significant impact. With the incorporation of both user-based and expert-based analytic methods, there can be a multidimensional portrayal of interface design issues in the context of the real-world problems faced.

Two of the main methods that are combined into a new analysis are cognitive walkthrough (CW) and the keystroke level model (KLM). The CW is a method that is amenable to extension and can be repurposed to study phenomena in a range of contexts. In its basic form, this method segments a task into a set of user actions, goals, and subgoals. Strengths and limitations are well understood (32). The KLM is a method that aims to predict user performance and aggregate a user's cognitive functions during interaction with an interface (32). This combination of CW and KLM methods results in a new analysis as part of the framework.

The combination of these two methods into a revised, innovative walkthrough process provides a thorough, comprehensive framework to assess the complexities involved in task completion by aligning the cognitive complexities associated with each action. This shows the impact that small, repeated actions have on documentation burden and efficient system use through specific interface design aspects. This combination also shows that small, simple changes in the interface can have a significant impact on clinical workflow.

1.2 Research Aims

Aim 1: Formulate the navigational complexity framework for identifying differences in EHR interface systems and their impact on task performance.

- Analyze and critique currently utilized methods used in assessing EHR-mediated workflow and usability assessments of interface design elements.
- Propose a novel framework for identifying areas of navigational complexity within EHR systems with the goal of resolve challenges identified in interface design.

Aim 2: Apply the proposed framework to the study of EHR-mediated workflows and validate whether it can differentiate performance in EHR-mediated workflow.

- Complete the analyses detailed in the navigational complexity framework in a pre-operative setting to demonstrate that the framework can differentiate design, improved usability, and minimal navigational complexity
- Apply to various systems with users performing two tasks: completing medication administration records and medication reconciliation at different clinical sites.

Aim 3: Extend testing of the framework to pre- and post-implementation of EHR systems and evaluate differences in performance across systems, sites, and tasks to determine whether the proposed framework is more insightful than traditional approaches.

- Apply the framework to EHR-mediated workflows collected during the implementation of a new EHR within a pre-operative setting

- Evaluate performance and efficiency for comparison and identification of bottlenecks and variations in workflow across system, sites, and tasks.

1.3 Outline of Dissertation Document

The introduction is an overview of the scope of the research, the aims and the research plan. In Chapter 2, a summary of literature regarding EHR-mediated workflow and implementation and the currently available methods used for analyzing usability and system interface design is presented. The advantages and disadvantages of both expert-based and user-based methods is analyzed. Chapter 3 presents the theoretical framework that was used to conceptualize the navigational complexity framework. Chapter 4 proposes the navigational complexity framework and expected outcomes. Chapter 5 relates initial testing in a pre-operative setting to assess task performance. Chapter 6 extends the framework validation to a pre- and post-EHR implementation process to evaluate the efficiency of the old EHR-mediated workflow compared to the newly implemented workflow.

2 THEORETICAL FRAMEWORK AND METHODOLOGICAL REVIEW

With widespread adaption of HIT, there is a need for a methodological framework that can leverage varying approaches to examining EHR-mediated workflows at a granular level. This collection of methods should be used to elucidate minor variations in design dimensions and reveal simple changes to support clinician's work and minimize complexities in system use. To achieve this, it is necessary to understand how clinicians complete their work and make decisions, how users interact with different systems across settings, and how the technology can assist the user best. CE, human factors (HF), human-computer interaction (HCI), and usability engineering (UE) theories and frameworks allow for a microanalytic evaluation of system design and their ability to assist or hinder clinician's EHR-mediated workflows. This chapter will review constructs from each of these theories and how they can be applied to the analysis of interface navigation and design.

2.1 Cognitive Engineering Theories and Frameworks

CE is an interdisciplinary framework for the development of principles, methods, and tools. It is used to assess and guide the design of systems to support human performance. CE highlights the discrepancy between the user’s goals and the physical controls embodied in systems (30). The main goal is to perform work more efficiently by providing an improved connection between the user and the system. CE has the ability to allow cognitive functions and associated interactive behaviors to be supported through system design such as user interfaces (43). One unique characteristic of CE is that it has a dual focus on different aspects of work: 1) complexities inherent to the domain and 2) strategies enabling the practitioners to cope with the demands of the domain (4,44). Because domain complexities and individual strategies are identified and separated, it is possible to distinguish strategies resulting from suboptimal design versus strategies for effective coping with complexities inherent to the domain.

With the dynamic nature of human use within computer systems, there is a need for systems to fit their area of work for the sake of the user and their workflow (45,46). Because of this increasing need, HCI has a need for a suitable theory that can conceptualize and support user perspectives for system design changes. Goal-directed design has been proposed as a methodology to address issues where different users of a product express a desire for different interface functions (47,48). Through the application of a goal-directed analysis of workflow and interfaces, the intention is to understand the basics of users' needs and the beahvior of a user to create an interface that satififies user workflow needs. The goal is to create user interaction strategies and crete a specific user model through structuring user interactions through their main goals throughout workflow (49).

By focusing on the user goals and interactions, the design of interfaces can be scrutinized and determine characteristic behaviors and goals. This goal-directed design also allows for modeling beahvior patterns and goals that users complete. The main advantage to utilizing the goal-directed approach to workflow analysis is that by situating user interaction strategies in the form of goals and indiivudal steps a user completed, the interactions to achieve these goals can be tailored for efficiency while easing user burden (48–50). When the goals of a user are understood for task completion, a strategy to achieving these goals can be created that translated directly into interactions within the system.

When executing the clinical workflow, CE can be leveraged to structure workflow into tasks, goals, and subgoals associated with the work process. Workflow is comprised of individual tasks completed by the appropriate role. When executing these tasks, there are a number of goals that users leverage as checkpoints to track their progress. To divide each of these goals into manageable steps, the user allocates the required actions of the goal to subgoals. These are the physical and cognitive processes embodied in the system. The cognitive processes in these subgoals are the three cognitive constructs mentioned in

Chapter 1: working memory, visual search, and perceptual-motor actions. The physical processes in these subgoals can be quantified through interactive behaviors. The goals and subgoals associated with a task vary by the individual and are known as individual microstrategies (30,51).

2.2 Human-Computer Interaction and Interactive Behaviors of Users

There are detailed documented problems in human-computer interaction (HCI) theories identifying suboptimal clinical work processes, especially in EHRs. The work of various researchers into HCI has revealed the same three main cognitive constructs previously mentioned as the most prominent: perceptual-motor activity, visual search, and working memory (36,52,53). Although all three elements are necessary for any task, certain task-system combinations may be more memory-intensive or require more in the way of perceptual and motor behavior (30).

When considering technology and how users interact with devices, there are two main components: the device into which user commands are inputted and the object that received the commands. The form in which information is presented by the technology to the user, the interface, facilitates functions or activities to be executed by the user, interactive behavior is combined into microstrategies. The different microstrategies developed by a user are a result of interface design features that influence the ways in which users reach their workflow goals. Although these differences in interface dimensions are small, by observing the individual microstrategies at an action-by-action level, bottlenecks in the workflow can be revealed (30).

Problematic interface interactions can carry cognitive consequences, such as the "keyhole effect," a well-documented problem in HCI research (36,54). The keyhole effect can occur when an abundance of information is made available through the narrow lens afforded by an interface. This is analogous to peeking through a keyhole in a door to see what is in a room. This problem can create a significant usability bottleneck that can have a consequent effect on workflow. A well-designed interface can place knowledge that exists in-the-world in a readily available location at the moment that a user needs it rather than a user having to retrieve it from in-the-head (51). There is a balance between the constructs priorities during system design.

More or less interactive behavior often can be required of a user based on system design. To determine that, task-system interactions can be observed to create the most user-friendly process. Users divide their cognitive resources between performing tasks and navigation, which is constrained by the pre-determined sequences of operations imposed by the system. There are two types of constraints put on users by a system: hard constraints and soft constraints. These constraints dictate the interactive behaviors completed by users. Hard constraints are non-negotiable actions within an interface that users must complete. Soft constraints offer flexibility in the process, seeking the fewest and most routine interactive behaviors.

2.3 Conclusions

There is a need for a framework that can evaluate how well technology can and should support users in a real-world setting (4). By combining the theoretical of HCI, microstrategies, and CE, a combination of methods can surface to act as an engine for discovery while presenting compelling findings regarding the issues users face. Although the frameworks presented here each focus on a single aspect of system design and user work, they only capture a subset of the issues in system interaction.

By drawing on all of these frameworks, a theoretically grounded methodological approach for elucidating navigational complexity can be created. The study of navigational complexity could benefit from a granular approach that captures the moment-by-moment experience of the user. A combination of quantitative and qualitative data could offer a method of higher precision and reproducibility. The framework proposed in this research could illuminate the nature of the design decisions and inform future design solutions at a granular level that stretches beyond the current methods and frameworks. The framework presented here could aid in identifying bottlenecks in EHR-mediated workflow and address the gap in knowledge of currently used, single-method approaches.

3 LITERATURE REVIEW

To effectively adopt HIT into practice, clinical workflow must be understood and analyzed from a user's perspective. This is especially true with EHRs, which can either hinder or facilitate clinical workflow (42,43). With the implementation of EHRs, the expectation is that there will be streamlined task processes, improved efficiency, and most importantly, enhances in system usability (33). However, a persistent problem that affects workflow is that EHR interfaces are unnecessarily complex and often confusing to use, compromising the user experience (26,33,55). These usability issues within interfaces are cited as a significant obstacle to widespread adoption and improvement (55,56). The chapter presents literature related to EHR-mediated workflow and methods used for analyzing usability and system interface design.

A number of different methodological approaches have been proposed to analyze EHR-mediated workflows through a single-method or multi-method approach. The current literature typically applies a single method to a single EHR-mediated workflow task in a single setting. The literature review presented here covers the methods used for analyzing usability and system interface design within EHR-mediated workflow analysis and the advantages and disadvantages of each method. The main areas of literature presented are as follows:

1) Problems with interface design, EHR-mediated workflow navigational complexity in systems, and the effects on the user
2) User-based and expert-based approaches used in assessing EHR-mediated workflow and interface design
3) Technologies and approaches available to assess EHRs and challenges faced when using a single evaluation method versus multiple methods

3.1 Problems with Interface Design, EHR-Mediated Workflow and Navigational Complexity and the Effects on the User

Interface design complexity often results in an information system providing poor usability, resulting in overall dissatisfaction with EHRs and increasing safety challenges and burden of use (57). Often, providers perceive EHRs as difficult to use, and usability analysts have cited issues that include confusing displays, lack of consistency and intuitive meaning of iconography, and illegible displays (58). A majority of EHR users complain that systems seems largely tailored for clinical transactions rather than clinical care, affecting patient safety due to inefficient and unintuitive interactions with the EHR (59,60). The usability issues cited, such as poor interface design aspects, can lead to increased cognitive load and can surface during interaction, causing disruptions to workflow and efficiency (61,62).

Often specific interface design aspects such as screen layout, information density, and widgets can contribute to inefficiencies within system interaction. Such poor interface design elements create a significant impact on efficiency and effectiveness in accessing and documenting patient information. These challenges surface most commonly when transitioning from one system or interface to another, causing disruptions to workflow and efficiency (62,63). To identify these challenges in design, there needs to be an effective process for evaluating EHR usability.

In a recent publication by Roman et al., EHR navigation was defined as interactions with the user interface presentation and controls that allow the user to locate and access the information they need within a system to complete a task (36). Roman et al. distinguish between two different types of EHR navigation: between-page navigation (action to move to a new page in an EHR) and within-page navigation (actions to move within a given page) (36). To add more theoretical background to the definition Roman et al. established, navigation should be guided by function that is constrained by its form. The form in which interface elements are presented can contribute to varying levels of complexity with system navigation, delaying workflow progress. There is considerable variation in form across EHRs for the same task, such as medication reconciliation (10,36). Optimizing the form in which information is displayed, accessed, and edited is predicated on identifying and understanding the flow of specific tasks. However, often these forms restrict the actions available to users during system interaction.

Systems, especially EHRs, often have constraints built into their design, allowing for a series of interactive behaviors to be performed to complete a goal or task. Microstrategies are often guided by specific interface design aspects and constraints through poor interaction. The constraints implemented by the system require a user to rely on working memory, a finite resource that, when utilized too often, diminishes human performance. There is a tradeoff between the level of interactions that can be stored in working memory to complete a task versus the intensity of tasks that can be completed. There is a belief that increased perceptual-motor actions effort, the skill of successfully obtaining and understanding information with the appropriate reaction, is favored over memory effort (64). An example of a high burden on working memory and a known issue contributing to suboptimal EHR design is crowded screen designs. Specifically, EHR navigation of different menu screens create a high memory demand in the navigation between the interface for task execution and increases the complexity of use.

To understand the microstrategies of users, there must first be a thorough analysis of the cognitive, perceptual, and motor operations used to complete a task (51,65). Comprehension of these microstrategies provides a better understanding of the complexities users face in interacting with an interface. This allows for redesigning of optimal systems, promoting efficient system use and maximizing patient safety. In a recent study, Ratwani et al. compared clinician's performance on a controlled task (using the same clinical cases) across systems and sites. The study found substantial differences in measures such as mouse clicks, duration, and error rate. The results highlighted the wide variability in the use of EHRs across sites and systems and the need for optimization. System assessments can provide unique insights into the user experience and identify features that exemplify best practices and those that do not meet that standard.

The rapid adoption of EHRs has created high variability in the modes of interactions of EHRs. This rapid adoption has surfaced unintended patient safety concerns particularly related EHR design and use in the form of work-arounds (66–69). These varying modes of interaction, couples with fast adoption rates, often facilitate unsafe conditions for a patient interaction (22). The detection of these patient safety concerns related to EHR use is difficult because they often not only involve EHR design and interface complexities, but also the individual user behaviors associated with system use and organizational characteristics (22,25,70). Studies that aim to observe patient safety concerns within EHR use is often one-sided, not considering the workflow of the setting, the individual users, and the complexities of the technology (22,37,71). These all can contribute to the origin of the safety issue within the system, relating back to not only technology-related issues but also workflow issues. While many studies identify complexities with system use, there is a need to shift these observations into actionable changes into designing a safer EHR

(22,70). It has been found that user interface designs can have a substantial impact on user productivity, adding burden to clinicians and minimizing

Several observational studies have identified interface complexities, the mediating effects that various EHR designs have on patient safety, and the impact on EHR-mediated workflow and, more importantly, interaction patterns during system navigation (37,72,73). Duncan et al. compared specific task performance on different EHR interface designs and the navigation and workflow involved with task completion, specifically in the medication reconciliation task (MedRec). The study characterized EHR-mediated workflow before a system-wide EHR conversion, comparing interface designs for task completion across two different EHRs (37,42). The interfaces were found to differ in modes of interaction and cognitive support based on specific interface design elements (10).

A recent study by Horsky et al. compared the accuracy of two different electronic medication reconciliation tools to determine the cognitive consequences of specific interface designs. It was found that significantly fewer errors were made in EHRs with single-column medication lists than systems with side-by-side lists. The authors suggested the need for MedRec tool usability testing and comparison tools for various EHR interface designs (74).

Plaisant et al. contrasted a conventional interface design with a novel design (Twinlist), using animations to split an interface versus an interface using side-by-side lists to compare task efficiency. Traditional comparative usability evaluations showed that Twinlist's multicolumn design facilitated the faster completion of MedRec with substantial reductions in the number of clicks (63). Tamblyn et al. designed and assessed the implementation of a new electronic MedRec tool to determine optimal functionalities by assessing the time spent on the task, providing insight into optimal interface design. Required modifications to the interface were identified, reducing task completion time by nearly half (75).

While there have been multiple studies that analyzed interface design aspects and their overall usability, usability also largely contributes to the EHR-mediated workflow in the use of these systems. To analyze both EHR-mediated workflow and interface usability, different approaches to analysis are required from the perspective of the user interacting with the interface. These should the form of user-based testing and expert-based evaluations of systems.

3.2 User-Based and Expert-Based Evaluation Methods for Assessing EHR Usability and EHR-Mediated Workflow

There is often tension during EHR usability evaluations and improvements between the systems efficiency and patient safety (42,60). There can be a balance achieved between these two pieces, a goal that the American Medical Informatics Association (AMIA) Task Force 2020 aims to achieve. One significant recommendation of the AMIA 2020 Task Force was decreasing documentation burden; poor system usability can significantly contribute to documentation burden. Poor usability can create barriers to clinical workflow due to a lack of consistency across interface design, generating interaction complexities during data entry and navigation. By modeling the steps in clinical workflow and assessing the associated interfaces, areas with high cognitive load and usability barriers may be further explored through comparative analysis. Comparative analyses of different interface layouts that clinicians utilize may yield valuable insights into the sorts of changes needed to streamline EHR design to enhance user performance (55,76).

Comparative system analyses can be used effectively and efficiently to assess usability. They are typically conducted in two categories: user-based testing and expert-based testing. Expert-based testing is conducted by usability experts, who systematically inspect EHR designs to identify design violations and may enhance the explanatory power of the empirical results of user studies (77). The methods leveraged include representational analysis (RA), KLM, and CWs. User-based testing is conducted by monitoring end-users utilizing the system in real-world settings (77). The methods leveraged include analysis of cognitive processes, interactive behavior measures, and clickstream data.

RA is the first of the three interrelated expert-based analysis methods used in the navigational complexity framework to model the completion of an EHR task while assessing task performance. RA describes and evaluates the appropriateness of the representations for a given task and a given type of user (33,39). The focus of RA is on the form of a section of a display, how it may impact cognition and its connection to the workflow. However, one of the main flaws with RA is that the dimensions that are used for analysis are based on a standard task taxonomy for computer vision tasks. While this taxonomy determines what interfaces are appropriate, it lacks the ability to evaluate which interfaces are appropriate for a specific task completed by a designated type of user (33).

The KLM analytic method evaluates the set of operations and the time required to complete a task. In the KLM model, there are six operators: key button press and release

(K), mouse pointing (P), moving hands to the home position on the keyboard or to the mouse (H), button press (B), mentally preparing to perform an action (M), and typing a string of characters (T(n), n x K seconds) (78). Each action has an estimated time for execution: K is 0.20 seconds, P is 1.10 seconds, H is 0.40 seconds, B is 0.10 seconds, M is 1.20 seconds, and T(n) is 0.20 * n seconds. Thus, the KLM model for a specific task can be constructed by identifying each operation needed to complete the task and summing together the execution time for each operation. The KLM, therefore, represents the time taken to complete a task if it were done with no errors or interruptions. The constructed KLM can then be compared with observed user data.

Saitwal et al. utilized KLM to evaluate the user interface of an EHR when completing 14 prototypical tasks across various interfaces to gather ideal task execution times (50). The goal of utilizing the KLM was to show the high percentage of mental operations required for complex interfaces and the long execution times. The results showed that if the clinician completes all tasks, the system is ineffective for users; nearly 50% of the time is spent performing mental operations during interface navigation and interaction.

We also (42) studied vital signs documentation and medication reconciliation tasks in the EHR, characterizing how different charting interfaces mediate task performances across clinical sites (55,79). Our study documented how the configuration of interface elements created unnecessary navigational complexities when interacting with the system. Markowitz et. al. employed graphical user interface design guidelines to create a MedRec prototype (80). The prototype was compared with two other MedRec systems using KLM.

The prototype also proved to be less cognitively taxing than the other systems, as measured by KLM analyses, showing nearly a 1.5-second difference between the prototype and the original system. The prototype, informed by design guidelines, was shown to be more efficient overall in completing MedRec (80).

CW is a commonly used method for analyzing interface complexity and usability (41,81). It involves characterizing a sequence of actions and goals for completing a task. To assess the cognitive aspects involved in a user's interaction with a system, the CW offers the advantages of tracking and logging user issues. The interactions between the user and interface are recorded, and the relationship between the goals the user has, the required goals to complete a task, and how the interactions with the system facilitate these goals are all shown in detail.

There are three main user-based, interrelated analytic methods for modeling the process of completing an EHR task while assessing task performance overall: cognitive processes, interactive behavior measures, and clickstream data. User-based methods are particularly important for revealing problems where the interface design affords more degrees of interaction freedom and where, within an interface layout, there are higher chances to observe greater variation in processes. Design tradeoffs often surface through the three main cognitive processes that can affect EHR-mediated workflow: visual search, working memory and perceptual-motor actions.

The severity of an interaction's complexity can often be revealed through the processes that mediate task performance. Interactive behavior measures provide insight into task performance with the goal of quantifying documentation burden. In this case, this is due to navigational complexity. These behaviors are typically represented in mouse clicks, screen transitions, and time to complete a specific step or series of steps when interacting with an interface. Clickstream data is user data modeled on a timeline showing the series of clicks users completed throughout task completion. This visualization clearly and concisely reveals the variations between individual users.

In many interactions with an application, hard constraints are imposed by the system. The subgoals in EHR-mediated tasks—for example, engaging a dialogue box—necessitate fixed patterns of behaviors and permit no degrees of freedom. Hard constraints should not be impacted by the host of variables, such as case complexity, that influence EHR-mediated workflow. Hard constraints can be described by expert-based methods. In contrast, soft constraints in the interface suggest which of the possible patterns are likely to be chosen and executed but may afford considerable latitude (65). These can only be revealed in user-based methods. Variation in the clickstream as evidenced in our results is indicative of users negotiating soft constraints. The pattern of behavior is subject to a range of influences beyond the interface including the individual differences of clinicians using an EHR.

While leveraging single methods for usability evaluations, there are benefits and drawbacks to each of these individual assessments (77). Single approaches do not provide a cohesive picture of usability and cannot answer every question regarding system design and use, only a subset. However, with the combination of multiple methods utilizing both experts and real-world users for analysis, a clear picture of bottlenecks in interface design and workflow can be identified and more effectively remedied from design, ease-of-use and patient safety standpoints.

3.3 Technologies and Approaches Using Single Versus Multiple Evaluation Methods

Expert and user-based methods can be used independently, as they have been in many studies, but employing them in concert provides a more comprehensive picture of navigational complexity. Expert-based methods provide guidance to the source of navigational complexity at a granular level and enhance the explanatory power of the empirical results of user studies. They can also be used to predict differences in system comparisons. User-based methods provide a real-world acid test for expert analyses and provide additional insights into navigational complexity. Expert-based methods are ideal for modeling relatively fixed navigational pathways: for example, where the interface determines the action sequence.

There has been research regarding the usefulness and necessity of leveraging multiple methods for analyzing interface usability and EHR-mediated workflows. One of the main issues that are faced in usability assessments is the selection of an appropriate method or the use of a combination of methods. The specific selection can depend on a number of factors, from resources available to insights desired (55,82,83). To assess usability problems, user-based methods and expert-based methods are used (37,55). While each of these methods is useful in a number of situations to identify interface complexities, many of the studies that utilize them focus on a single measure that cannot provide a complete view of the barriers to usability (37,55). A combination of techniques will complement each other and would provide more insight into system design solutions (77).

There have been multiple studies that address the selection of the appropriate method to effectively assess EHR interface usability and bottlenecks in workflow (77). Walji et al. found that a combination of usability methods is superior when identifying EHR issues compared to a single approach. With user-based methods, deeper insights into the specific problem with interactions on computer systems that users face is provided. Soft constraints—loose guidelines for interaction steps—can be identified with user-based methods while hard constraints—rigid paths of interactions—can best be described by expert-based methods. Because system design enforces both soft and hard constraints, to evaluate EHRs, the combination of different usability and workflow testing techniques that complement each other is necessary (77).

EHR navigation for a single task is a relatively finite topic, and there are a small number of routes to task completion. Often to assess the routes to task completion provided by the interface, a single method of analysis is leveraged to discover the bottlenecks in workflow from a user standpoint, facilitated by the interface for task completion. The literature has provided justification that a combination of expert-based and user-based methods is more effective and efficient in identifying these bottlenecks in workflow. Through the combination of multiple methods of analysis, a clear picture of problems with interface design and workflow can be identified and more effectively remedied from a patient safety standpoint by improving the design of EHR interfaces.

3.4 Conclusions

Navigational complexity has an undeniable impact on the burden experienced by clinicians when using EHRs. While expert and user-based methods provide specific insights, there is a gap in the usability issues that may be identified in interface design by a single method. To clarify the range of complexities involved in system interaction and determine the impacts of cognitive performance, expert-based and user-based methods are combined in this work in a navigational complexity framework.

The navigational complexity framework has the goal of identifying cognitive tradeoffs and challenges involved in EHR-mediated task completion through a combination of usability analysis methods (36). The combination of quantitative and qualitative data offers precision and high reproducibility. The framework leverages a range of CE methods (4) and visualizations to identify complexities at a granular level and characterize individual users, interfaces, and clinical sites (37). The next chapters detail the proposal and validation of the navigational complexity framework.

4 PROPOSAL OF THE NAVIGATIONAL COMPLEXITY FRAMEWORK AND THE ASSOCIATED METHODS

4.1 Introduction

During usability assessment, summative assessments are performed with the intention of validating application usability in the hand of the intended users in the context for which it was designed, performing usual tasks (84). The range of methods employed for assessing usability can vary from expert reviews or end user's involvement. However, no single approach can identify a software's range of usability problems. There is currently a lack of research that can combine user participation with usability analyst expert feedback to create an effective framework for detecting a range of usability issues from those different perspectives (77,84). A combination of methods can complement one another to provide a complete picture of the usability issues faced (77,82).

With the understanding that EHRs will enhance productivity, healthcare institutions have invested large amounts of money, effort, and time in implementing them. However, there is often dissatisfaction that EHRs do not support cognitive workflow and information needs, creating a difficult user experience. One of the main culprits of difficult user experience that contributes highly to navigational complexity is display fragmentation largely because of its effect on EHR-mediated workflow and the need to move through the entire system for a single task. Display fragmentation of functions and screens for a task highlights that interacting with certain system complexities set in place by design itself require division of cognitive resources.

In an ideal system, there should be a clear navigation path to accessing needed information with information tools minimizing EHR-mediated workflow complexities. Systems should enable user control and freedom by allowing for a user's focus to be on the desired task rather than how the tool itself is used (85). However, hard and soft constraints embedded in the system design often create excessive navigational complexity. Because of the number of hard constraints, there is little room for adaptive methods to minimize navigation for clinicians during patient care. Where soft constraints are implemented, there is variation in task completion steps that individuals leverage in the form of microstrategies.

If these microstrategies can be observed and modeled, the path in which users optimize interaction while minimizing the cost of interactions can be highlighted, and interface changes can be made. By scrutinizing seemingly small interface design differences through a micro-analytic approach, we can better identify and quantify user's microstrategies and examine their impact on task completion. This can lead to effective changes in interface design to provide ease-of-use to users and maximize EHR-mediated workflow efficiency.

A solution to this is the navigational complexity framework proposed here. This framework aims to employ methods for capturing, analyzing, and visualizing EHR use and clinical workflow of clinicians in a number of different clinical settings (39). The main players involved in data analysis are the clinician of focus, the researcher completing data collection, and the usability expert completing the analysis. This is achieved through a combination of expert-based and user-based methods to explore differences in task-specific EHR interfaces and the associated EHR-mediated workflow. The framework is unique in that not only does it provide traditional expert-based and user-based methods but also combines these into a new, single form of analysis. The expert-based KLM and cognitive walkthrough methods are combined with the user-based cognitive processes into a modified walkthrough leveraging all three.

This new proposed analysis allows for alignment of user goals and subgoals, user mental operators and estimated task completion and cognitive processes. With this new, modified walkthrough, there are two main outcomes generated that were previously missing. These outcomes are the categorization of cognitive constructs per user steps and a quantification of the frequency of these cognitive constructs. By categorizing and quantifying the occurrences of cognitive constructs, complexities within the interface can be identified and tradeoffs between the occurrences can be minimized. While it is not possible to judge an interface, the outcomes generated from the combination method aims to make it more clearly understood in the context of other design choices and protocols driving a process.

When combining user-based and expert-based analyses into the combination method, clinical users can be engaged when performing tasks to understand the impact of interface design real-time. With input from an expert review standpoint, traditional usability evaluations can be applied. The use of these two different approaches also create a holistic comparison tool to identify design issues and areas of high cognitive load. Evaluations from these two standpoints support one another.

The micro-analytic approach involves a more granular level of analysis of both the user and the system behavior. It can characterize interactions with the system at a moment-to-moment level with a high level of detail (33), considering the user's microstrategies in task completion. It also enables the modeling of task behavior with a higher level of precision, requiring relatively few subjects. This chapter introduces the details of the navigational complexity framework and explains the two main categories of methods, their associated data streams, and the newly formed codified walkthrough. (37). This chapter corresponds to Aim 1 of the thesis.

The framework presented here served as a data collection guide regardless of the clinical setting of task of focus compared to traditional expert-based approaches. Anyone interested in assessing the impact that interface design has on navigation and EHR-mediated workflow can follow the stepwise process of applying the framework to the enterprise's clinical setting of interest. The guidebook details the resources required for data collection and analysis as well as providing detailed instructions for applying the framework. There is no requirement of design knowledge or experience during data collection and analysis, and the results can be easily interpreted and translated to interface design changes.

When applying this framework to any of the EHR-navigational problems that an organization chooses to focus on, there are requirements for data collection prior to analysis. First, there is a need for screen capture software, such as Morae, to gather data in-situ observations of clinicians using their EHR that can be used for analysis. Second, there is the requirement of having access to a clinical setting. In order to gather data, access to enter and observe clinicians in-situ is required for data collectors as well as permission to record actual patient cases within the setting of focus. The third requirement is an option for data storage and security with the generated observations files. Direct observation files are large and because they contain patient information, a high level of security is required. Once these conditions are met, data collection can begin, and the framework analysis can be performed.

4.2 Navigational Complexity Framework Analysis Methods

The navigational complexity leverages a combination of qualitative and quantitative data to offer a higher level of precision. This combination can provide a deeper understanding of the interaction complexities within the interface associated with task completion. Observational data is analyzed using user-based methods and expert-based methods. Figure 1 is a graphical representation of the methods use broken down by category. User-based evaluations are done through direct observation of users in-situ to determine end user's routines for task completion. These methods include clickstreams, behavioral measures, and cognitive processes. Clickstream data maps large clusters of user activity that are aligned with the subgoals and individual actions within task completion.

Behavioral measures can highlight the controls users exercise for interacting with interface elements in terms of physical actions. This gives insight into the physical and cognitive effort required to navigate an interface in the form of mouse clicks, screen changes, and time. These constructs are qualitative and aim to characterize difficulties faced by users across different interface elements.

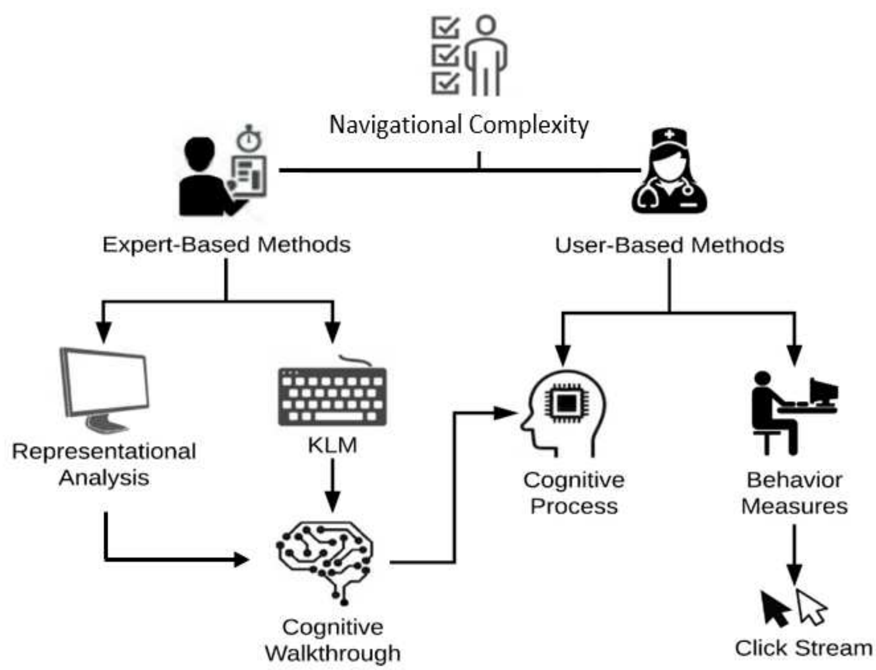


Figure 1: Expert-Based And User-Based Methods Of Navigational Complexity Framework.

Expert-based methods engage usability experts that assess design based on standard cognitive and usability principles. These evaluations are completed through qualitative methods. Analytic data is generated and used for analysis. These methods include RA, KLM, and CW. The goal of RA in the context of this framework is to identify different interface representations, outcomes, and task difficulties based on the representations (33). This can be used in a granular analysis of the information displayed on an interface based on a pre-determined taxonomy. KLM has been shown to act as a reliable indicator of the effort required by a user to navigate an interface (78,86). KLM is a basic technique that provides insight into the ideal world but cannot and does not leverage user data to support the claims it makes regarding user actions. The CW can evaluate how well an interface design can support a user in completing a specific task. This is done by identifying the complexities that user faces within individual steps of system navigation.

User-based methods involve clinical users performing tasks in the real-world setting. These methods include behavioral measures, clickstream, and cognitive processes. Behavior measures are quantitative measures of total time, mouse clicks and screen change to complete a task. Clickstreams model interaction complexities users' face by showing the series of clicks required for task completion and overall task efficiency. This visualization of user data has the primary goal of showing variation across individual users, systems, and clinical sites. Cognitive processes are a means of characterizing cognitive complexities that exist for task performance. There are often tradeoffs between these constructs. These constructs are largely qualitative aspects that are observed during system use and the tradeoffs have not yet been quantified in a single analysis.

User-based and expert-based methods complement one another to capture different system constraints and individual microstrategies. When the two are combined into a single form of analysis, they give insights that neither can achieve alone. A modified walkthrough is created that combined the expert-based KLM and CW and the user-based cognitive processes. This walkthrough includes goals, subgoals, as well as a description of the sequential process, physical actions involved, the ideal time to complete the task, and characterization of demands on cognitive processes.

The goal of this modified walkthrough is to explain how the interface form constrains workflow and how it is manifested in user behavior measures. The walkthrough looks at small differences in interaction and user behaviors to surface meaningful changes to be made at an action-by-action level. This combination of methods provided an estimation of the time to task completion, given a relatively optimal set of steps in an ideal setting. The KLM and cognitive walkthrough are able to identify functions associated with display elements, while the pairing of the cognitive processes provides insight into the tradeoffs between the mentioned cognitive constructs that the display elements facilitate. Although the cognitive processes are largely qualitative measures, by quantifying the number of occurrences a new analysis is generated. This quantification identifies areas within the interface where high cognitive construct tradeoffs exist.

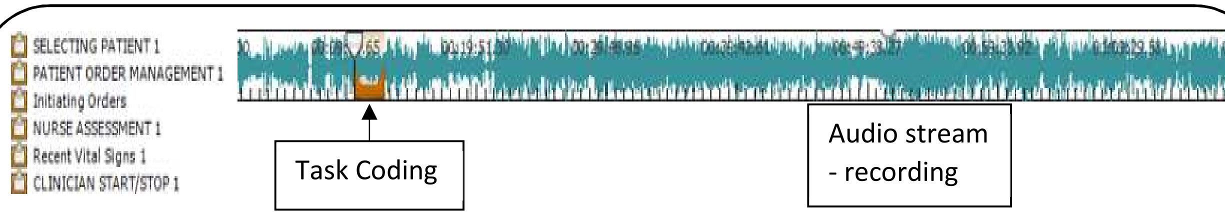
The generated qualitative methods can result in quantitative data that can be interpreted and used to make meaningful changes to workflow. Without quantitative data, the qualitative methods shown here have no concrete measurement that can be leveraged. For example, from the direct observations (e.g. Morae video software recordings), interactive behavior and frequencies of task execution can be generated. From the clickstream, grouping of high mouse click occurrences can be identified for tasks. For the cognitive constructs, the frequency and categorization of the occurrence of constructs is generate. This data is generated from the different data streams generated from the navigational complexity framework.

4.3 Data Streams Generated During Navigational Complexity Framework

The data streams used in the analyses are presented in Figure 2. The figure illustrates how the temporally-based user data was aggregated and combined to understand task complexities at a more granular level in novel ways. Initially, tasks were segmented, and analytics were generated for each task using a video analytic screen-capture software (Figure 2, section A). Once tasks were identified, RA was completed on the interfaces leveraged by users for task completion through screen captures of these interfaces (Figure 2, section B). Individual user data in the form of mouse clicks were then used to generate individual clickstream data for each occurrence of the task. Individual lines of the clickstream each represent an instance of the task (Figure 2, section C). The combination KLM/cognitive walkthrough method was created to show the goals, subgoals, and actions associated with individual steps to complete a larger task (Figure 2, section D) (53,72). A description of each data stream is provided below.

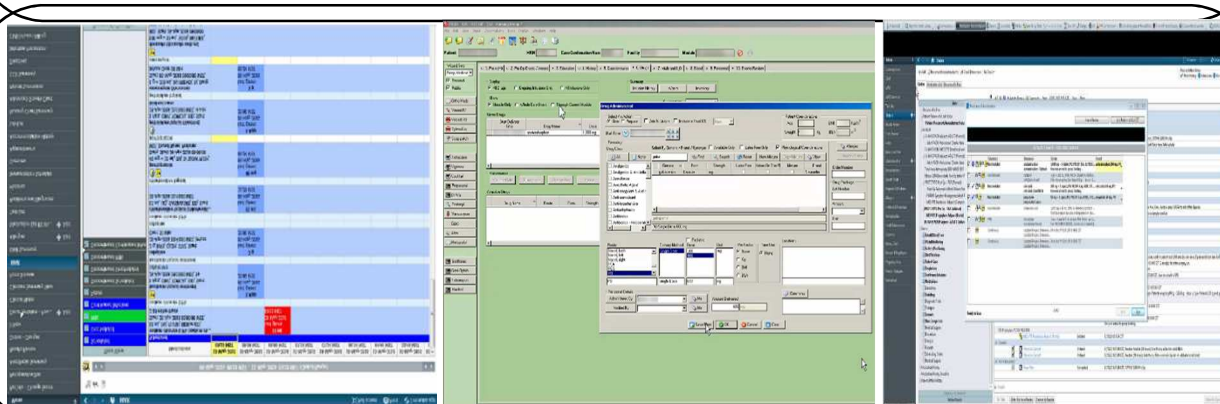
Figure 2A represents manual task coding of screen captures of EHR activity. Direct observations are leveraged by clinicians, mainly nurses, and interactive behavior measures are calculated based on system use. These analytics include the number of task occurrences, mouse clicks, screen changes, and time to complete a task. Figure 2B represents the application of RA applied to the individual interfaces navigated through task completion. These interfaces are those used by a clinician completing EHR-mediated workflow tasks. Areas of poor usability of navigational complexity are identified along with any associated interface elements. Once the interactive behavior measures are generated, and interface elements are identified, interactive behavior measures were then converted into clickstream data for each user see in Figure 2B. This is shown on a timeline with a point representing each time a user initiates a mouse click on the interface. Clickstream data is used to mark the beginning and completion of specific subgoals related to task execution. This connects the clickstream to both the representational analysis (spatially) and the walkthrough (temporally). Finally, to understand the cognitive demands associated with clusters of activities, the KLM/cognitive walkthrough is completed. This generates ideal time to task completion as well as aligns goals and subgoals of users with interface locations that can then be compared to the user-generated time to task completion.

A

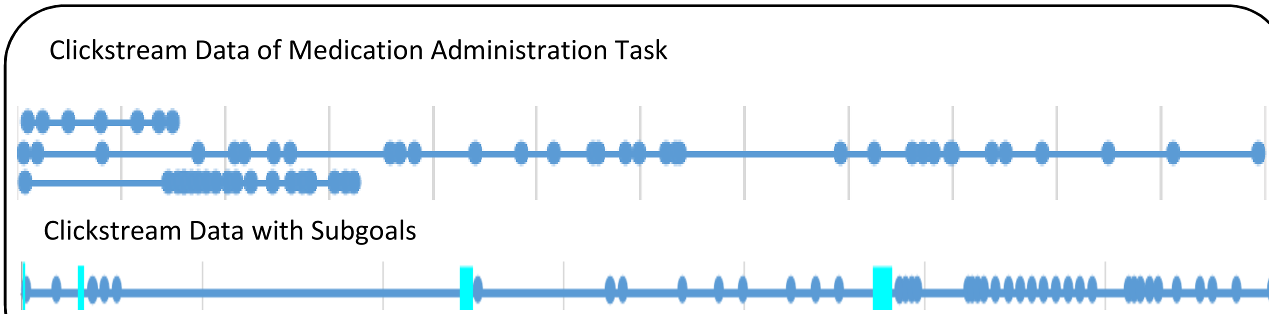


Patient	Task	Instances	Time	Mouse Clicks	Screen Changes
1	MAR	2	106 (114)	28.75 (33.12)	7.00 (3.54)

B



C



D

Cognitive Process	Description	Operation	Time (Sec)
Visual Search Working Memory	Locate "Ortho Meds" choice	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to " Ortho Meds " choice	P [Point]	1.1
Perceptual-Motor	Click on " Ortho Meds " choice	B [Mouse]	0.1
System Response: Generates "Drug Administered" screen			

Figure 2: Data Streams Of The Navigational Complexity Framework

4.4 Stepwise Process of Applying the Navigational Complexity Framework

The process of applying the navigational complexity framework involves three phases: understanding the clinical setting of focus, application of the framework and result interpretation. The understanding of the clinical setting of focus provides a basic description of the overall workflow of the area of focus including players involved, paper artifacts, physical layout where the workflow is executed and enterprise guidelines that may influence workflow. This knowledge is gained through interview with key informants from the clinical setting focus, clinical walkthroughs, and preliminary observations.

Once the description of the workflow of focus is completed, the framework, can be applied to the workflow of focus. Completion of the framework involves direct observations of clinicians using their EHRs in the real-world clinical setting through screen capture utilizing a software that runs in the background of clinician's computers. An observer with a hand-held camera was also present during the data collection. Once data collection is completed, the analysis process detailed in the navigational complexity framework is applied including user-based analysis, expert-based analysis, and the combination method of the framework. Once analysis is completed, the results are interpreted in the form of interface design changes that can be made to improve workflow efficiency.

4.4.1 Morae Video Capture

When applying the navigational complexity framework, there pre-processing data preparation takes place in order to complete data analysis. The raw data collected and prepared is direct observation data, in the form of screen capture, of clinicians using their system in-situ. Once collected, a clinical task list is created, and the observations are segmented per task occurrence. Following task segmentation, tasks are reviewed for integrity, and the task of focus is isolated, and the analyses are applied.

The main tool used for collecting direct observation data is called Morae ™ video analytic software. Morae provides screen capture recordings of EHR use as well as mouse movement, clicks on the screen, and screen transitions. The software records the clinician users' on-screen actions, providing a set of analytics and audio and video recording of the clinicians' hands via a webcam. This software runs in the background on a desktop while EHR-mediated workflow is completed, capturing all interactions on the screen. Figure 3 shows an example of the software. An observer with a hand-held camera is also present during the data collection to record points of interest during observations. Additionally, to gain context of the entire workflow of the specialty of focus, walkthrough tours of the environment were completed. This is a guided tour, captured by video recording, of the work environment by an experienced clinician showing the department workarounds, artifacts, and actors involved in the clinical workflow.

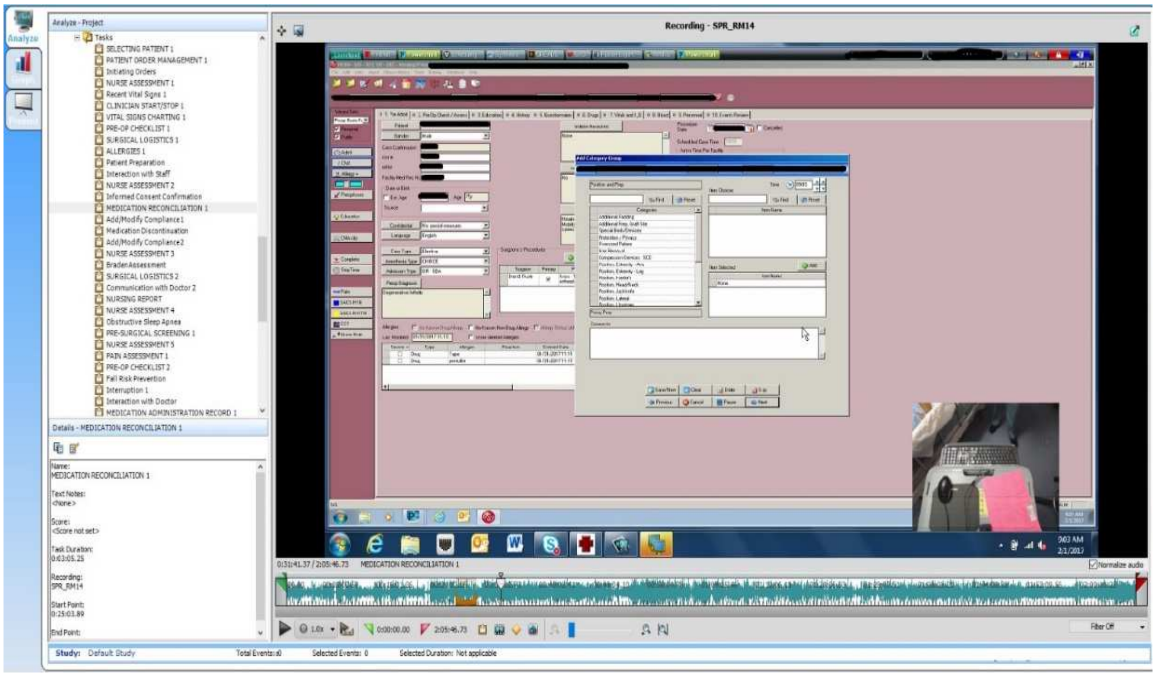


Figure 3: Morae Video Analytic Software Used For Screen Capture

4.4.2 Clinical Task Segmentation

In order to segment the clinical tasks that clinicians complete properly and effectively, a task list of associated tasks from the clinical and EHR-mediated workflow must first be created. This allows for a clear delineation of where individual tasks start and stop. In order to develop a comprehensive task list, there should be a review of observational data collected of currently implemented EHR-mediated workflow, sequential breakdown of EHR activities, and review of policies applicable to the specific site and setting of focus. Following task list creation, categorization of the individual tasks takes place. Once segmented, the user-based and expert-based methods can be applied. Figure 3 shows a sample clinical task list showing main tasks and associated sub-tasks. An example of a clinical task list is seen in Figure 4.

Discharge Planning/Social Services

- **Discharge Scoring System**
- **Current Living Environment**
- Cultural Practices
- Support System
- Advanced Directive

Pre-Surgical Screening

- Rashes, opening wound (Specials soap use)
- Antiseptic Shower, etc.
- Antibiotic Obtaining
- Request Site Marking
- **Additional Measurements for Surgery**
- Travel and Exposure
- **Patient Verification**

Surgical Logistics

- **Hospital Based Communication (For family)**
- Surgery Time
- Check Surgery Schedule
- **HUC Communication (ARZ)**
- **Precaution/Identity bands**

Surgical Patient Education

- Fall Risk
- Smoking Risk

Nurse Assessment

- **Identity Validation**
- **H&P Validation**
- **Informed Consent Confirmation**
- **Obstructive Sleep Apnea**
- **Recent Vital Signs (BP, Breathing Rate, Heart Rhythm, Head/Neck/Waist Circumference)**
- **Patient Skin Inspection/Pressure Sore (Integrity, Temperature, Moisture, Color)**
- **Listing Details**
- **Procedure Confirmation**
- **Contact Physician**
- **Medication Administration**
- **Medication Management**
- **Braden Assessment (EU)**
- **Modified Mayo Score**

Medication Reconciliation

- **Current Medication List**
- **EOP Message Order Review**
- Outpatient Orders
- **Medication Discontinuation**
- **Medication Search/Details**
- **Add/Modify Compliance (Last Dose Taken)**

Clinician Start/Stop

- RN Start
- RN Stop

Pain Assessment

- **Pain Scale Explanation**

Infection Prevention

- **Contact Infectious Control**

OBGYN/PREG Assessment

- **Age Verification (Over 14 and under 18)**
- **OBGYN Status**
- **Pregnancy Assessment**

Pre-Op Checklist

- **Tobacco Use Screening**
- **Adaptive Devices Screening (Hearing Aid, Dentures, etc.)**
- **Nutrition Screening**
- **Review Labs Review**
- **Fall Risk Prevention**
- **Pre-Op Checklist**
- **Nursing Care Plan**

Selecting Patient

- Searching Clinic Number
- Assigning Relationship (EU)
- Launch Status Board (Epic)

Medication Administration Record (ARZ)

- Medication Administration
- **Medication Documentation**

Active Patient Reminder Worklist

- Chart Summary View (Patient)
- Worklist Charting (Progress Charting)

Psychosocial Assessment

- Emotional Status
- Perceptions
- Mental Alertness
- Cultural Practices
- Teaching Methods
- Coping Technique

Immunizations

- Current Immunizations

Patient Order Managements (ARZ)

- **Discontinue/Deactivate Orders**
- **Activate Orders**
- **Initiating Order**

IV Charting (ARZ)

- **IV Placement**

Vital Sign Charting

Patient Assignment to Room

Nursing Report

Best Practice Advisory

Task List

Patient Needs and Services

Allergies

Figure 4: Example Of Clinical Task List Used For Task Segmentation

4.4.3 Data Analysis Application

Both the expert-based methods and user-based methods are applied independently to the direct observation data. This includes completion of interactive behavior measures (mouse clicks and screen changes), cognitive walkthroughs and KLM and clickstream analyses. Once completed, the data from the cognitive walkthrough and KLM can be align and the cognitive constructs can be assigned to each user step. This analysis can be completed on the clinical task of focus.

4.5 Discussion

While user-based and expert-driven methods can be used separately, the innovation of the framework can be seen through the combination of the KLM, cognitive walkthrough, and cognitive processes analytic methods. The goal of this combined method was to examine how specific goals and subgoals are leveraged when working through the steps of a task and their associated physical and cognitive actions. The modified walkthrough consists of the goals within a task, subgoals used as progress markers to work through a goal, physical actions associated with the subgoals, and the cognitive process it takes to complete these subgoals. The combination of these methods into a modified walkthrough provided insights into the specific actions and cognitive aspects involved with goals and subgoals.

There is general use of a single method that can only identify a small portion of usability issues that exist due to the limit of scopes taken in the analysis. With the use of the framework, a wider scope of analysis can be achieved and provide a deeper understanding of issues within interface design. Although the framework is initially proposed, there needs to be validation of the framework in tasks and settings. Initial validation is needed to allow for refinement of the framework and to determine if the correct set of methods were chosen. The next phase of validation requires applying the framework to a wider setting to confirm the feasibility and generalizability while confirming the ability to identify bottlenecks in workflow in multiple systems, sites, and users.

There are some limitations that are also carried with this framework. The microanalytic approach applied here enables the cross-reference subgoals derived from the walkthrough with clickstream data for a single clinician to identify task segments that are problematic. We can further characterize the problems in terms of interface elements employing a representational analysis and yield meaningful data with few participants. It does not include the impact of expertise or experience, which can significantly impact performance. As such, it is a very useful but not a sufficiently precise measure.

One of the main strengths of this methodology is the use of multiple data streams to identify the impact that interface design elements have on EHR-mediated workflow because together, they provide a thorough understanding of the complexities involved with task completion. The comprehension of these user microstrategies provides a better understanding of the complexities users face in interacting with an interface, allowing for the tailoring and redesign of maximally optimal systems, promoting the most efficient and patient safety. There is a small but steadily growing body of research comparing EHR systems (4,17,76) that can provide unique insights into the user experience and identify features that exemplify best practices, as well as those that do not meet that standard.

This framework varies from traditional user-centered design and expert-based approaches in that there is still a focus on the user, however, the framework does not take an iterative approach. It acts as a data collection and analysis guidebook to identify design issues experiences real-time and propose solutions in a single cycle. The framework also involves clinician users, usability experts and designers where user-centered design only involves designers. There is also a combination of qualitative and quantitative data in the framework compared to user-centered and expert-based approaches that utilize a single form of analysis.

Additionally, when compared to traditional frameworks leveraged in HCI, the navigational complexity framework aims to bridge the divide between static usability evaluation (e.g., as reflected in usability inspection or lab-based usability testing studies) and workflow by focusing specifically on navigational complexity. There is currently no absolute measure to quantify complexity, but the framework proposed a comparative approach to the study of EHR use as a starting point for characterizing relative navigational complexity.

A micro-analytic approach to modeling EHR-mediated workflow, as employed in the above work, can help optimize HCI most effectively. This approach incorporates analytic measures that focus directly on the elements of the interface and the task with measures of interactive behavior. It also employs constructs such as perceptual-motor actions, visual search, and working memory associated with different users' microstrategies, the series of individual steps to complete a task, which can lead to meaningful characterizations of interface complexity. The focus in this work is on EHR-mediated workflow and not exclusively on usability, although many methods common to usability studies were employed.

4.6 Conclusion

Navigational complexity within EHRs has an irrefutable impact on the burden clinicians experience. The proposed navigational complexity framework aims to model the navigation of EHR-mediated workflow. Different interfaces differentially mediate task performances, as reflected in interactive behavior. Through the proposed combination of methods, design tradeoffs can be surfaced, and changes to the interface can be executed. The proposed framework has been implemented in two different validation phases within the surgical setting: a single EHR-mediated workflow task and the pre/post-implementation on a new EHR to determine its accuracy in identification, generalizability, and scalability. Chapters 4 and 5 discuss in more detail the use of the framework in those settings.

The framework acts as a guide for capturing direct observations and proposing changes to interface design elements that affect task performance. The framework can be applied to any clinical setting, site or system. The framework is designed to be applied to wherever EHR-navigational problems exist in healthcare. The framework advises analysts on the appropriate data collection software and access to clinical settings, data storage and security requirements and appropriate analysis for proposing improvements to the interface to minimize navigational complexity and improve EHR-mediated workflow.

5 VALIDATION OF THE NAVIGATIONAL COMPLEXITY FRAMEWORK WITH A SINGLE EHR-MEDIATED WORKFLOW TASK: MEDICATION ADMINISTRATION RECORD

5.1 Introduction

In this chapter, the framework described in Chapter 3 is applied in the process of identifying the complexities in navigation variation across clinical sites and individuals for framework validation (37). This chapter corresponds to Aim 2 of the thesis. The framework has been applied to a larger research study, the Registry of Operations and Tasks (ROOT) project, a Mayo-Clinic funded research program aimed at studying workflow practices before and after a large-scale EHR conversion. The project is designed to support an enterprise-wide standardized practice and EHR implementation across all Mayo Clinic geographic regions. To confirm that the framework, utilizing a combination of methods, performs as expected when applied to EHR-mediated workflow, it was applied to an individual clinical task, medication administration record (MAR). The goal was to determine the framework's validity of performance assessment when incorporated into a larger research study of the pre-operative setting.

During the validation phases, the main area of focus was on the nursing patient check-in process in the PreOp setting because of three main advantages associated with this care setting. The first is that the PreOp workflow is relatively routine and constant, with the focus of one nurse being on one patient. The tasks for each patient are standardized across nurses. The second advantage to the PreOp workflow is that there was a single player completing the workflow, the nurse. While coordination activities did take place, the nurse responsible for that patient completed all documentation within the EHR on that patient. The third main advantage to selecting the PreOp workflow for framework validation is that there is a heave documentation workload with frequent use of the EHR. The EHR-mediated workflow is information intensive, and all information-seeking and documentation took place at the bedside, within the EHR. Because of these advantages, the PreOp setting was selected as the most feasible site for framework validation.

Various data collection methods were leveraged, including rapid ethnography interviews, video capture, screen capture, photos, and log files. Duncan et al. (10) used video-analytic methods to contrast the EHR interfaces, employing usability quantifiers such as task duration, mouse clicks, and screen transitions to characterize the difference of medication reconciliation tasks across sites. Grando et al. leveraged a series of combined methods to understand variation in patient and provider EHR-mediated workflows and interactions within interfaces in the Mayo Clinic Phoenix PreOp setting (87). Grando et al.

(88) described a triangulation methodology integrating observational data with process mining of log files to characterize broad patterns of communication and workflow among nurses fulfilling different roles in PreOp.

The framework was validated by applying it to a single EHR-mediated workflow task, MAR in the PreOp setting, to determine its effectiveness when compared to using a single method for evaluation. MAR is a report completed during the PreOp process that serves as a record of all medications or drugs administered to patients throughout their care (89,90). The goal of applying this framework to a single task is to determine that more thorough and in-depth insights into EHR-mediated workflow are provided when leveraging multiple methods versus a single evaluation method. By applying a micro-analytic approach, there can be better identification and quantification of variation in processes and examine their impact on task completion. Once the framework is validated on a single task, it can be expanded to a broader spectrum of EHR-mediated workflow. Because the ROOT project documents clinical workflows and determines changes in efficiency, the framework was applied to the data collected at different clinical sites to determine workflow changes and interface differences in clinical settings.

5.2 Clinical Settings

The initial validation phase of the framework was conducted in the PreOp setting at three Mayo Clinic regional campuses: Mayo Clinic Hospital, Phoenix, Arizona (AZ); Mayo Clinic Hospital, Jacksonville, Florida (FL); and Mayo Clinic Health System-Eau Claire Hospital, Eau Claire, Wisconsin (WI). Participants included 11 PreOp nurses across all sites and a total of 15 distinct patient cases. In the Arizona campus, the primary tool used for charting was Cerner SurgiNet. All patient information was accessed and updated through this application, along with patient tracking. In Florida, the main tool used for charting was Cerner SurgiNet, with the additional use of Cerner PowerChart for completing the MAR task. In the Wisconsin campus, the primary tool used for charting was Surgical Information Systems (SIS).

5.3 Data collection and analysis

Observations were of surgical staff performing their everyday work in-situ on a variety of patients in a PreOp setting between 2016 and 2017. The computer software Morae™ 3.3 was employed for video recording. This video analytic software was used to capture workflow. The data was collected over a period of two weeks at each site. The software records the clinician users' on-screen actions, providing a set of analytics (e.g., mouse clicks, web-page changes, etc.), and audio and video recording of the clinicians' hands (e.g., use of paper documents, checklists) via a webcam. An observer with a hand-held camera was also present during the data collection to record points of interest during observations. A total of 14 hours of video recordings were captured across 11 different nurses over ten days at the three different clinical sites, which are presented in this work. When possible, nurses voiced their thoughts as they performed the task (think-aloud protocol).

In the Arizona campus, the primary tool used for charting was Cerner SurgiNet. All patient information was accessed and updated through this application, along with patient tracking. In Florida, the main tool used for charting was Cerner SurgiNet, with the additional use of Cerner PowerChart for completing the MAR task. In the Wisconsin campus, the primary tool used for charting was Surgical Information Systems (SIS).

The analytic framework discussed in chapter 3 was applied by leveraging the expert-based and user-based following data collection. The methodological approach of the navigational complexity framework was applied to video captures of clinicians performing the PreOp EHR-mediated workflow. The expert-based methods were comprised of representational analysis, KLM, and cognitive walkthrough, while user-based methods involved cognitive processes, interactive behavior measures, and click stream data.

5.4 Results

As detailed in Chapter 3, the steps of the navigational complexity framework were performed, starting with task segmentation followed by the completion of both the expert-based and user-based. This included utilizing screen-captured data from clinicians, performing clinical task segmentation, and applying the user-based and expert-based analysis. The analysis can then be leveraged to identify inefficient interface design. The analysis presented here is also a validation of the framework to prove that the combination of methods provides more insight into design than a single-method approach.

Table 1 for SurgiNet (Arizona) represents the flow of task completion in the form of the new combination analysis described in Chapter 3. The table is organized to present goals and subgoals involved with task completion. Each of these goals and subgoals includes a description of the sequential process or flow, actions involved, time to complete this part of the task, and characterization of demands on cognitive processes. These are coordinated with the results of the RA with interface representations that highlight specific design elements and representations of the information shown in Figures 3, 4, and 5. These results indicate that the tasks are realized in different ways across the systems, which is elaborated below, present observational or user-centered data, explaining how the interface forms constrain EHR-mediated workflow and how that is manifested in interactive behavioral measures. The table also illustrates an integrative methodological approach.

Table 1: Function And Form For MAR Task For Three EHR Systems

Goals and Subgoals	Form		
	Arizona	**Florida**	**Eau Claire**
Goal 1: Transition to MAR Screen			
Subgoal A: Locate "MAR" Menu Choice	Select menu column	Tab at top of the page	Locate choice using dropdown menu under wizard sets
Subgoal B: Select "MAR" menu choice Selection	Select from medication list, generated by screen	Select from pop-up window, which displays all medications	Select from dropdown menu leading to pop-up window
Goal 2: Document Medications			
Subgoal A: Select the desired medication	Select from medications displayed in columnar format	Select medication from in pop-up, no additional action required	
Subgoal A*: Document medication start time			Select medications available with dropdown menu
Subgoal B: Enter details of the medication	Enter medication details on previously generated pop-up window. Enter via	Automatically upload via barcode scanner	

		static buttons and dropdown choices		
	Subgoal B*: Modify personnel details			Select staff member name entering medication into MAR
	Subgoal C: Save modified medication details	Select checkmark symbol	Click “Sign” button on the bottom of the generated pop-up screen	Click on next button
	*Denotes alternative subgoals unique to a particular EHR system			

5.4.1 User-Based Results: Task Interactive Behavior Measures

Table 2 represents the observed interactive behavior measures when completing the MAR task across all sites. These measures provide insight into task performance and aim to quantify the burden of documentation from navigational complexity placed on clinicians. In turn, these are used as comparisons to the measures derived from the expert-based methods to determine how the observed compares to the ideal. This difference in procedure is seen in the mouse clicks, screen changes, and time to complete a task. These measures are reflective of navigation executed and steps taken during task completion. For example, Arizona and Wisconsin had higher mouse click counts at 28.7 (33.12) and 27 (0.82), while Florida required 12.7 (2.17) clicks. It can be seen that, based on time to task completion, there is general consistency in time, meaning that each system contains individual complexities during use.

Table 2: Interactive Behavior Measures For The MAR Task Across All Sites

Task completed/ All cases)	Mean (SD) of Time (sec)	`Mean (SD) of Mouse Clicks	Mean (SD) of Screen Changes
Arizona (6/8)	106 (114)	28.75 (33.12)	7.00 (3.54)
Florida (4/7)*	97 (39)	12.75 (2.17)	10.50 (1.66)
Eau Claire (3/3)	176 (46)	27 (0.82)	20.3 (2.6)

**The estimates include both systems used in the Florida site*

5.4.2 User-Based Results: Task Clickstream Data

To further explore the interaction complexities distinct users' face, clickstream data was collected for individual users and modeled on a timeline showing the series of clicks through task completion. The main goal of this visualization is to show variation across individual users. These can be seen in Figures 6, 7, and 8, showing clickstream data for Arizona, Florida, and Wisconsin. In Arizona, there are short occurrences that show a smaller amount of mouse clicks compared to other cases. This mainly shows that some instances require the clinician to document a single medication given at the time rather than an extensive series of medications. Based on the example of goals and subgoals expressed in Table 1, large clusters of activity (clicks) can be explicitly aligned to subgoals and actions performed. Figure 6 compares the clickstreams for multiple patient cases, a timeline of occurrences of mouse clicks throughout the cases. This visualization not only allows for the comparison of users across a single site but compares users across multiple sites.

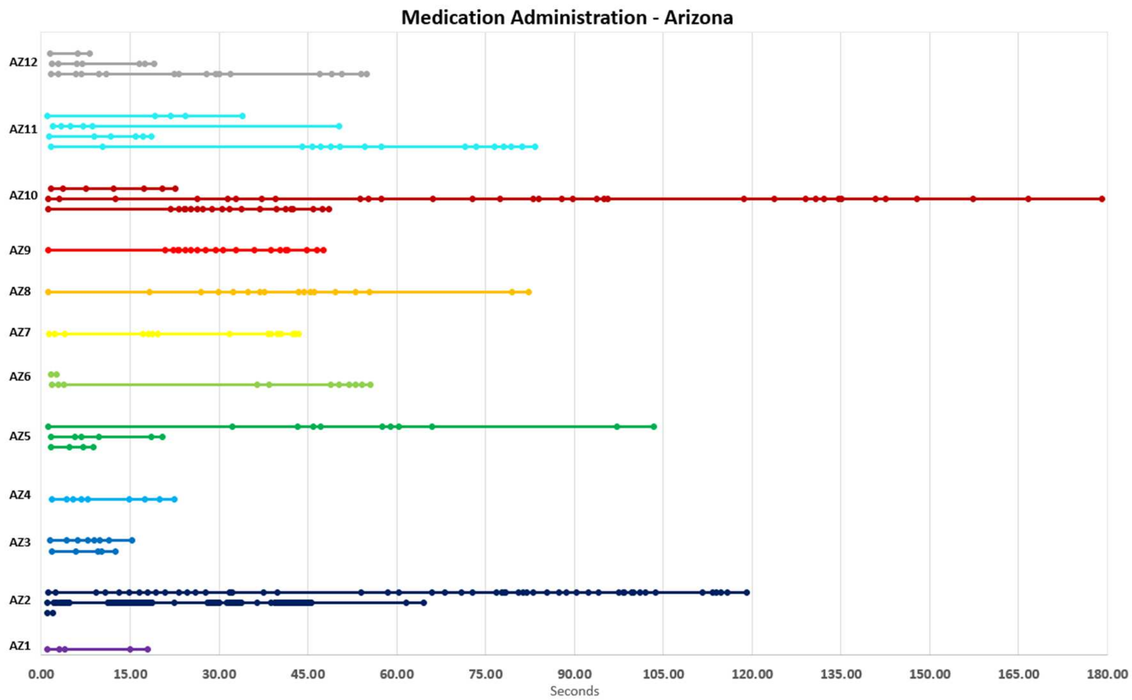


Figure 5: Clickstream Data Per User Of The MAR Task In Arizona.

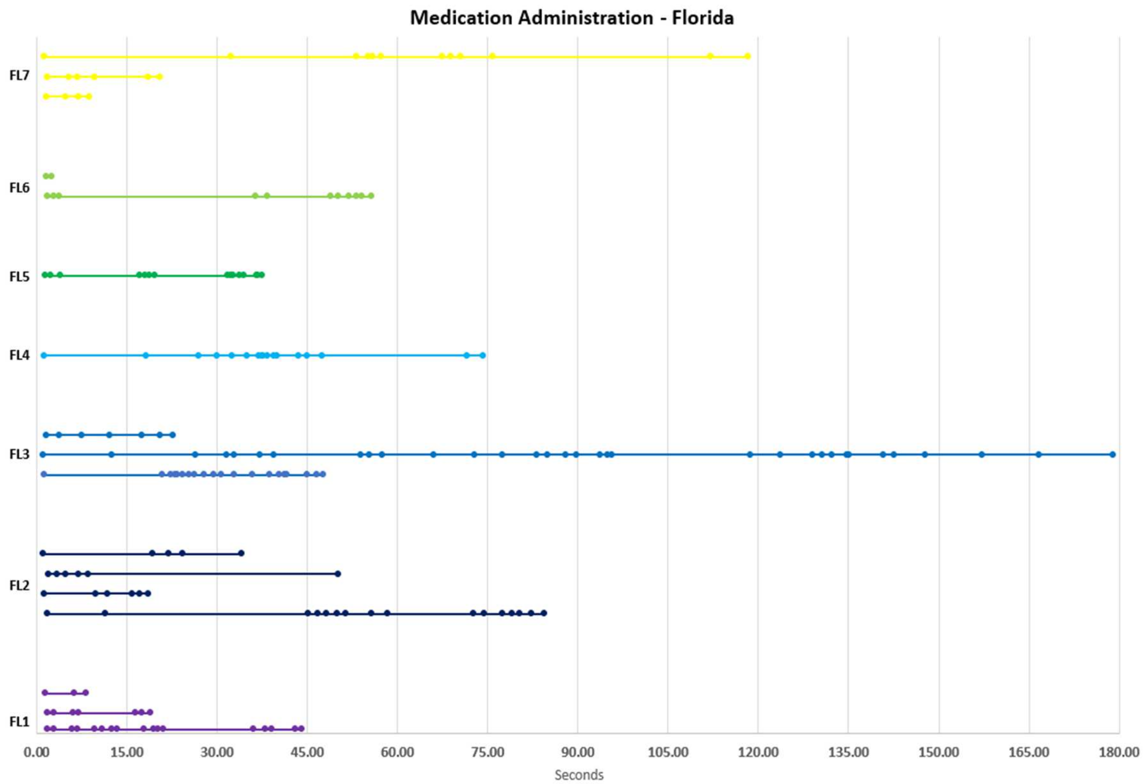


Figure 6: Clickstream Data Per User Of The MAR Task In Florida.

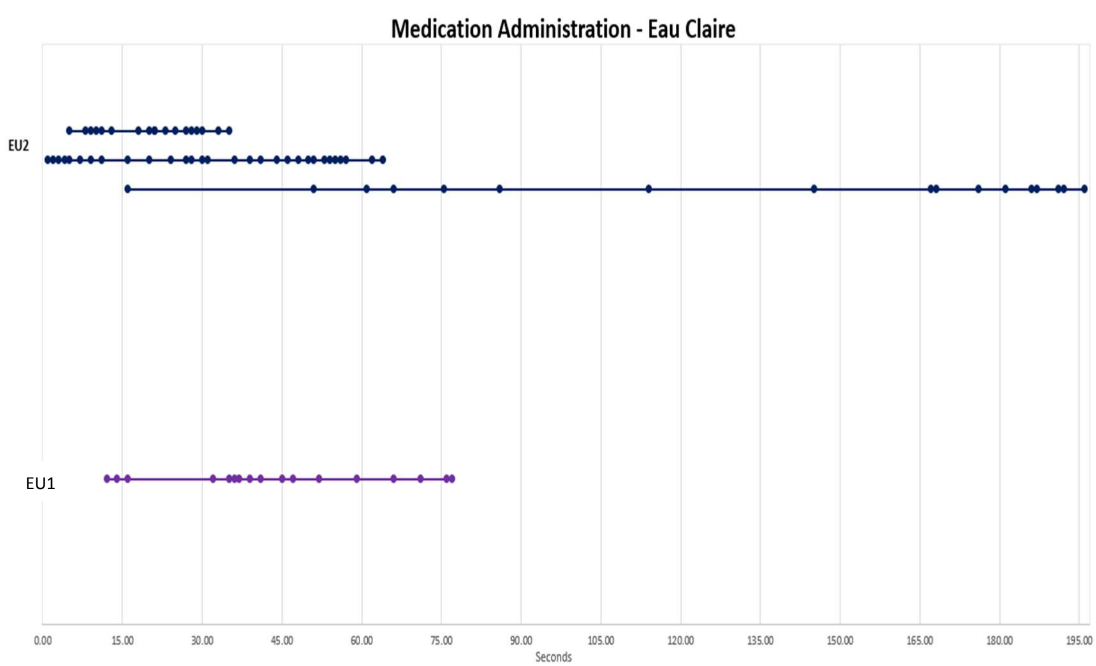


Figure 7: Clickstream data per user of the MAR task in Eau Claire.

5.4.3 Expert-Based Results: KLM

When comparing the observed and KLM measures for the entire MAR task, there are some interesting differences (Table 4). Notably, we observed that nurses could rapidly negotiate the screens and could anticipate where to click next with minimal search. The differences seen in Arizona and Florida are primarily due to the physical actions involved with the MAR task, while Wisconsin utilizes a different system, which required different steps overall. It should be noted that the sample is small, and the variation is considerable.

Arizona and Florida yielded a KLM measure estimate of 15.6 and 16.4 seconds, while Wisconsin resulted in 18 seconds. These are generally compared in line with the observed user times for Florida and Wisconsin with 16.39 and 18.94. However, in Arizona, the observed time was significantly shorter than the KLM estimated at 10.3 seconds, meaning the model over-estimated the required time to complete the MAR task. KLM does not take individual expertise and experience into account. For example, experience using a system can significantly reduce the visual search time. Notably, we observed that nurses could rapidly negotiate the screens and could anticipate where to click next with minimal search. The differences seen in Arizona and Florida are primarily due to the physical actions involved with the MAR task, while Wisconsin utilizes a different system, which required different steps overall. It should be noted that the sample is small, and the variation is considerable.

Table 3: Mean Task Completion Time, Actual Time, And KLM Estimates For MAR.

Task completed/ All cases)	Mean (SD) of Time (sec)	Actual Time (sec)	KLM (sec)
Arizona (6/8)	106 (114)	10.37	15.6
Florida (4/7)*	97 (39)	16.39	16.4
Eau Claire (3/3)	176 (46)	18.94	18

5.4.4 Expert-Based Results: CW

A cognitive walkthrough for the MAR task was performed in Arizona, Florida and Eau Claire, each leveraging different information systems. These can be seen in Tables 4, 5 and 6. The analysis showed that the MAR tasks generally require the same amount of work to complete. Arizona and Florida both sites required 3 sub-goals to complete the main task while Eau Claire required 4 subgoals. The subgoals associated with task completion and generally similar across sites in that they require navigating to a medication list and entering details of a medication. However, in Eau Claire, there is an extra step of entering the details of the user completing the MAR task. This adds the extra subgoal during task completion, adding extra actions required for a user to take. There are constraints placed on the user by the system that require this subgoal to be completed rather than a workaround to simplify the process.

Table 4: MAR Cognitive Walkthrough - Arizona

Goal: Complete medication administration record task
Start State
Screen: SurgiNet IView screen
Subgoal: Navigate to MAR Screen
Action: Click on "Orders-Charges" Choice under Menu Options
System Response: Orders menu generated
Action: Select "MAR" from menu
System Response: MAR interface generated
Subgoal: Document appropriate medications
Action: Select medication
System Response: Medication details screen generated
Action: Select medication status of "Given" or "Not Given"
System Response: Medication status marked on screen
Action: Select reason for giving from "Reason" dropdown menu
System Response: Medication distribution reason saved in system
Subgoal: Save entered medication details
Action: Select checkmark for saving medication details
System Response: Medication detail entry is saved

Table 5: MAR Cognitive Walkthrough - Florida

Goal: Complete medication administration record task
Start State
Screen: PowerChart Home screen
Subgoal: Navigate to MAR Screen
Action: Choose appropriate medication administration tab
System Response: Generates "Medication Administration" screen
Subgoal: Document appropriate medications
Action: Select appropriate medication
System Response: Generates medication details page
Action: Physical scanning of medications
System Response: Known medication details imported into medication administration screen
Action: Select appropriate medication details
System Response: Selected medication details stored on screen
Subgoal: Save modified medication details
Action: Select save sign button on "Medication Administration" screen
System Response: Pop-up screen saves medication details and cycles to next medication

Table 6: MAR Cognitive Walkthrough - Eau Claire

Goal: Complete medication administration record task
Start State
Screen: SIS Patient Information Screen
Subgoal: Navigate to MAR screen
Action: Make selection from dropdown menu
System Response: Medication list categories generated
Subgoal: Select "PreOp Medications" Selection
Action: Click on "PreOp Medications" Selection
System Response: Preop medication list generated
Action: Select medication administration button
System Response: Generates "Drug Administered" screen
Subgoal: Document medication "Start Time"
Action: Modify medication start date/time
System response: Date/time saved in record
Subgoal: Modify personnel details
Action: Enter personnel details
System Response: Personnel details saved
Action: Select save button on "Drugs Administered" screen
System Response: Pop-up screen saves medication details and cycles to next medication

5.4.5 Expert-Based Results: Representational Analysis

The goal of the representational analysis is to isolate and analyze the individual interfaces that users navigate through and interact with to complete different goals of a task. Every health IT system has different representations and interface designs for screen layouts. The results of the representational analysis are shown here to provide insight into used and unused design aspects. In Arizona, using SurgiNet, the option for navigating to the MAR screen is located in a menu column for quick transitions between various sections of the EHR. This selection is labeled as "MAR" (Figure 3A). In Florida, using PowerChart, the process varies slightly. The "Medication Administration" tab is shown at the top of the page with a series of other shortcut tabs (Figure 4A). In SIS, a dropdown menu is utilized, titled “Wizard Sets”, that allows for navigation through interface sections (Figure 5B). In all three systems, the only step involved with this subgoal is to locate the system-specific option within the interface. The KLM estimated time is 1.2 seconds to perform this action and subgoal. This makes demands on visual search cognitive processes as the clinician must search through a dense interface for the desired menu option.

In Florida, using PowerChart, the “Medication Administration” tab is selected, and a newly generated pop-up window displays all medications for the selected patient (Figure 4C). In SIS, the mode of interaction varies, where a selection from a dropdown menu is made rather than a menu choice, generating a new pop-up window where medication details are entered (Figure 5C). In both SurgiNet and PowerChart, the KLM resulted in single actions and similar total times, with two steps required in the action. The system requires users to point to the desired menu choice and click on it, requiring an estimated 1.2 seconds to complete both actions. This facilitates both the perceptual-motor actions and visual search cognitive process, with perceptual-motor actions being prominent, requiring users to move the mouse and click the selection. In SIS, the mode of interaction within the interface differs widely, requiring two separate actions with a total of 8 steps. Users select the appropriate option from the dropdown menu and then make a second selection to navigate to the MAR section on the generated pop-up screen. In SIS, there are roughly equal amounts of perceptual-motor actions and visual search cognitive processes. This is primarily due to the number of actions necessary, requiring users to perform more physical actions and requiring users to locate several menu options within the interface.

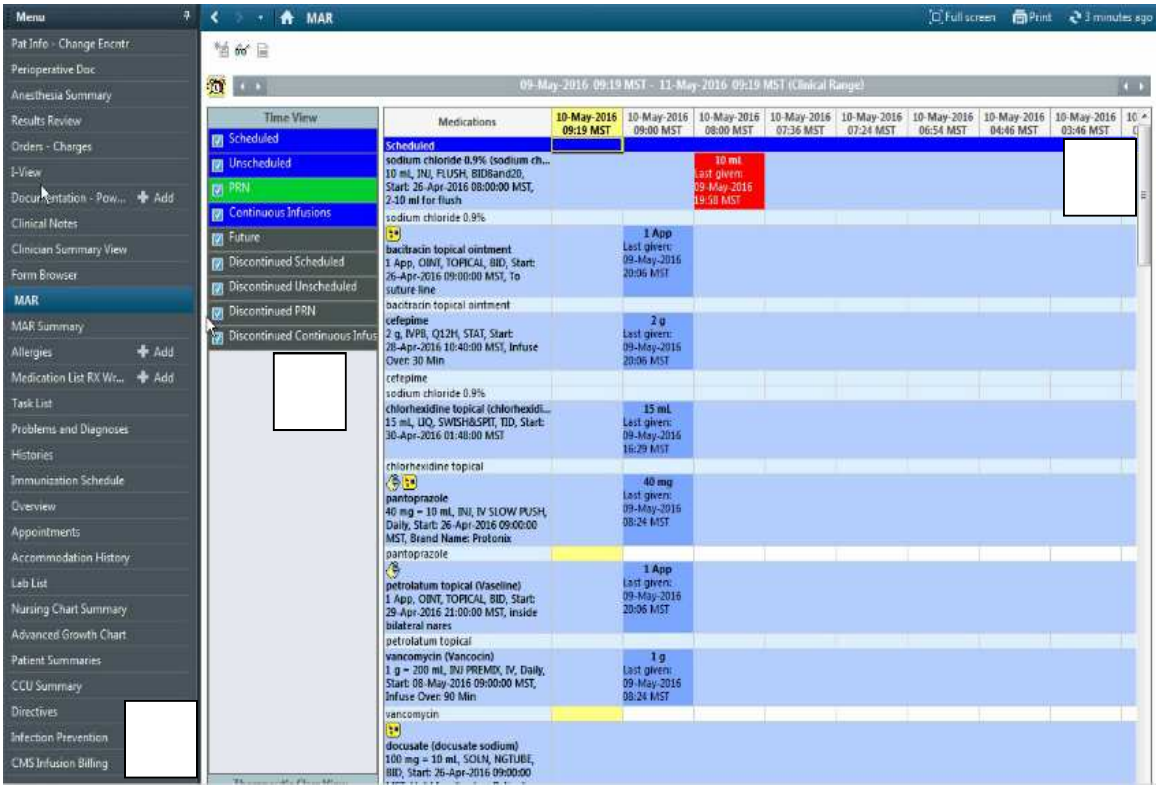


Figure 8: Medication Administration Interface Used In Arizona.

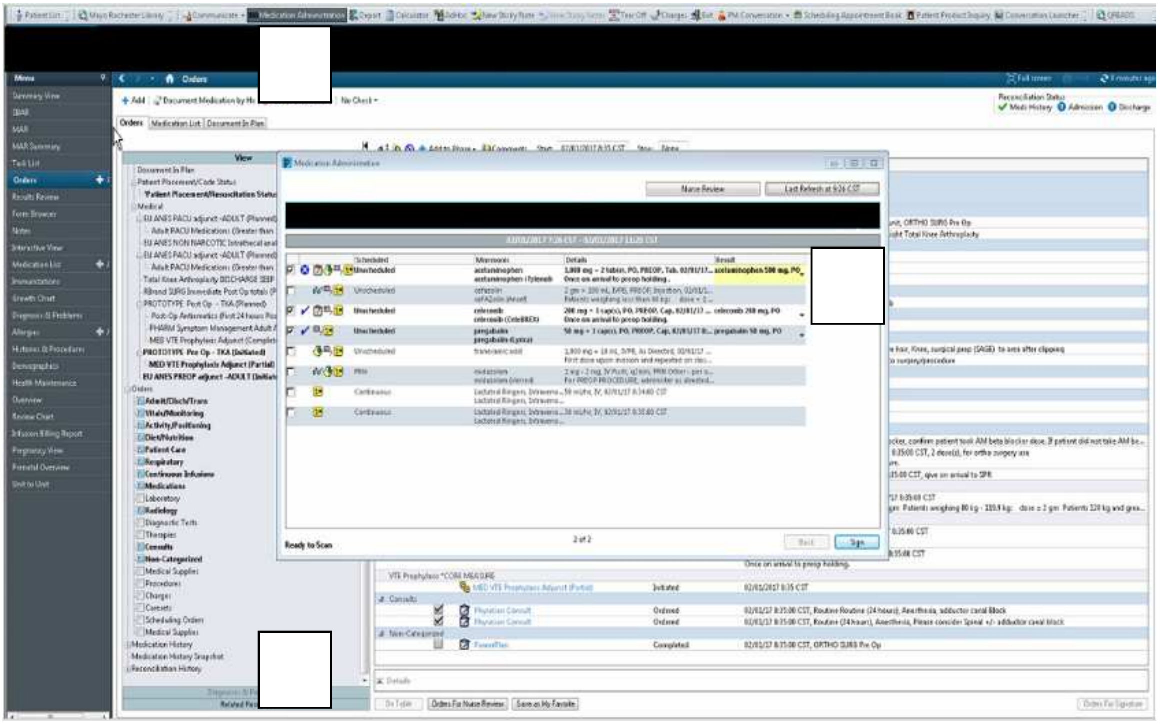


Figure 9: Medication Administration Interface Used In Florida.

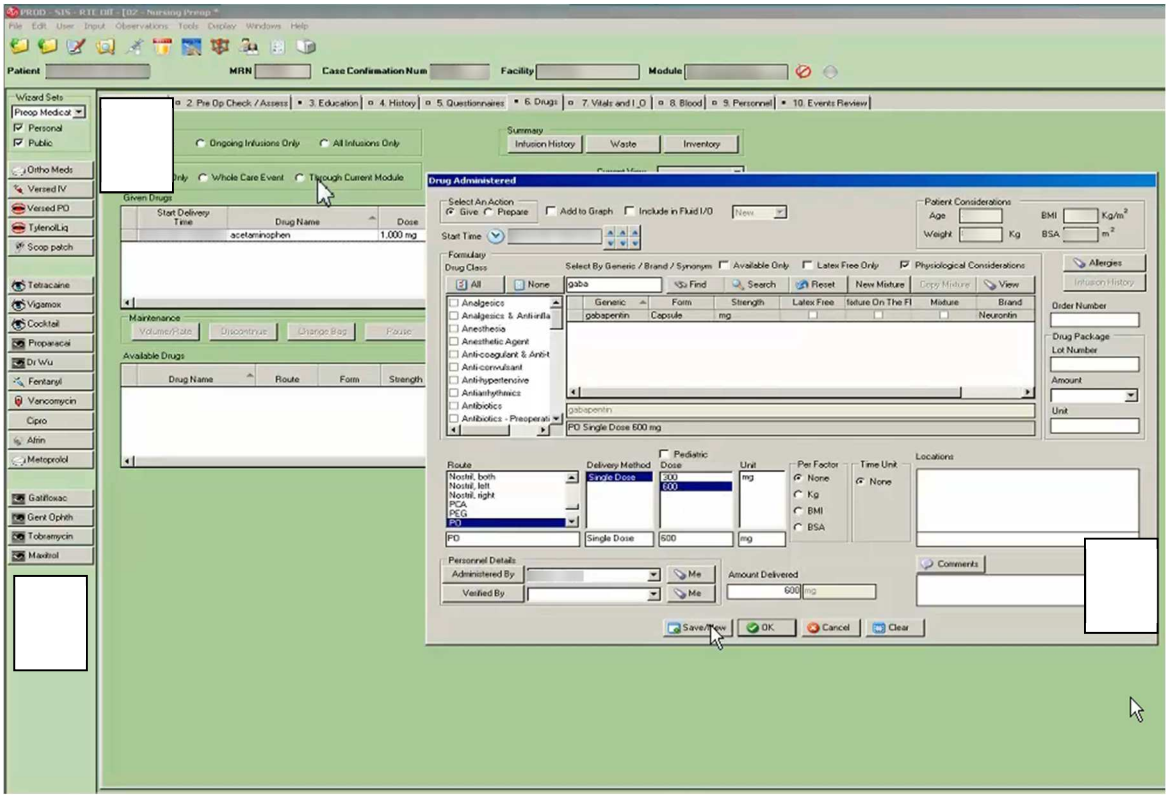


Figure 10: Medication Administration Interface Used In Eau Claire

5.4.6 Combination Method: Cognitive Walkthrough/KLM Combination

Table 7, 8 and 9 presents the cognitive walkthrough/KLM combination for Arizona, Florida and Eau Claire showing goals, subgoals, actions associated with the MAR task. The analysis included a description of the sequential process or flow, actions involved, time to complete this part of the task, and characterization of demands on cognitive processes. This is completed by aligning the expert-based cognitive walkthrough goals and subgoals, KLM actions and estimated action times, and user-based cognitive processes. The new outcome generated from this modified walkthrough are categorization of cognitive processes per user steps as well as the frequency of cognitive process occurrence.

These results were coordinated with the results of the RA with interface representations that highlight specific design elements and representations of information. There is a total of twelve occurrences of visual search, seven occurrences of working memory and twelve occurrences of perceptual-motor activities in Arizona. In Florida, there are a total of eleven occurrences of visual search, six occurrences of working memory and twelve occurrences of perceptual-motor activity. In Eau Claire, a total of thirteen occurrences of visual search, nine occurrences of working memory and twelve occurrences of perceptual-motor activity occur.

Table 7: Combination Method: Arizona Cognitive Walkthrough/KLM

Goal 1: Transition to MAR Screen			
Subgoal A: Locate "MAR" Menu Choice			
Action: Search Menu for the "Orders-Charges" Selection			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Visual Search Working Memory	Locate "MAR" button	M [Locate]	1.2
Subgoal B: Select "MAR" menu selection			
Action: Click on "Orders-Charges" Choice under Menu Options			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Perceptual-Motor Visual Search	Point to " MAR " button	P [Point]	1.1
Perceptual-Motor	Click on " MAR " button	B [Mouse]	0.1
System Response: Generates MAR			
Goal 2: Document appropriate medications			
Subgoal A: Select the desired medication			
Action: Select medication			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*

Working Memory	Determine what medications are appropriate to document	M [Locate]	1.2
Visual Search Working Memory	Locate the appropriate medication	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to the appropriate medication	P [Point]	1.1
Perceptual-Motor	Click on the appropriate medication	B [Mouse]	0.1
System Response: Medication detail pop-up screen generated			
Subgoal B: Enter details of the medication			
Action: Enter medication information			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Visual Search Working Memory	Locate “Not given” checkbox	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to “Not given” checkbox	P [Point]	1.1
Perceptual-Motor	Click on the “Not given” checkbox	B [Mouse]	0.1
Visual Search Working Memory	Locate appropriate “Reason” dropdown menu	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to appropriate “Reason” dropdown menu	P [Point]	1.1
Perceptual-Motor	Click on the “Reason” dropdown menu	B [Mouse]	0.1
Visual Search Working Memory	Locate appropriate reason for “not given”	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to appropriate reason for “not given”	P [Point]	1.1
Perceptual-Motor	Click on appropriate reason for “not given”	B [Mouse]	0.1
Subgoal C: Save modified medication details			
Action: Select Save selection			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Visual Search Working Memory	Locate save checkmark	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to save checkmark	P [Point]	1.1
Perceptual-Motor	Click on save checkmark	B [Mouse]	0.1
System Response: Saves medication details			

Table 8: Combination Method: Florida Cognitive Walkthrough/KLM

<u>Goal 1</u>: Navigate to Medication Administration Interface			
Subgoal A: Locate the "Medication Administration" tab			
Action: Choose appropriate medication administration tab			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Visual Search Working Memory	Locate "Medication Administration" tab	M [Locate]	1.2
Subgoal B: Select "Medication Administration" tab			
Action: Click on "Medication Administration" tab			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Perceptual-Motor Visual Search	Point to "Medication Administration" tab	P [Point]	1.1
Perceptual-Motor	Click on "Medication Administration" tab	B [Mouse]	0.1
System Response: Generates "Medication Administration" screen			
<u>Goal 2</u>: Document medications			
Subgoal A: Enter medication details			
Action: Select appropriate medication			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Perceptual-Motor Visual Search	Point to appropriate medication	P [Point]	1.1
Perceptual-Motor	Click on appropriate medication	B [Mouse]	0.1
System Response: Generates medication details page			
Action: Physical scanning of medications			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Perceptual-Motor Working Memory	Scan distributed medication with barcode scanner	Ph [Physical]	2.0
System Response: Known medication details imported into medication administration screen			
Action: Enter remaining medication details			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Working Memory	Determine the medication administration site	M [Locate]	1.2
Visual Search	Locate "Site" section	M [Locate]	1.2

Working Memory			
Perceptual-Motor Visual Search	Point to “Site” section	P [Point]	1.1
Perceptual-Motor	Click on the “Site” section	B [Mouse]	0.1
Visual Search Working Memory	Locate appropriate site	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to appropriate site	P [Point]	1.1
Perceptual-Motor	Click on appropriate site	B [Mouse]	0.1
Subgoal B: Save modified medication details			
Action: Select save sign button on “Medication Administration” screen			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Visual Search Working Memory	Locate the “OK” button	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to “OK” button	P [Point]	1.1
Perceptual-Motor	Click on the “OK” button	B [Mouse]	0.1
Visual Search Working Memory	Locate the “Sign” button	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to “Sign” button	P [Point]	1.1
Perceptual-Motor	Click on the “Sign” button	B [Mouse]	0.1
System Response: Pop-up screen saves medication details and cycles to next medication			

Table 9: Combination Method: Eau Claire Cognitive Walkthrough/KLM

Goal 1: Navigate to Medication Administration Screen			
Subgoal A: Locate the “Preop Medications” Selection			
Action: Make selection from dropdown menu			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Visual Search Working Memory	Locate "Wizard Sets" dropdown	M [Locate]	1.2
Subgoal B: Select “PreOp Medications” Selection			
Action: Click on “PreOp Medications” Selection			
Perceptual-Motor Visual Search	Point to "Wizard Sets" dropdown	P [Point]	1.1
Perceptual-Motor	Click on "Wizard Sets" dropdown	B [Mouse]	0.1

Visual Search Working Memory	Locate "Preop Medications" choice	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to "Preop Medications" choice	P [Point]	1.1
Perceptual-Motor	Click on "Preop Medications" choice	B [Mouse]	0.1
Action: Select medication administration button			
Cognitive Process	Description	Operation	Time (Sec)
Visual Search Working Memory	Locate "Ortho Meds" choice	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to " Ortho Meds " choice	P [Point]	1.1
Perceptual-Motor	Click on " Ortho Meds " choice	B [Mouse]	0.1
System Response: Generates "Drug Administered" screen			
<u>**Goal 2**</u>: Document appropriate medications			
Subgoal A: Document medication "Start Time"			
Action: Modify medication start date/time			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Working Memory	Determine the date/time medication given	M [Locate]	1.2
Visual Search Working Memory	Locate the "Start Time" location	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to "Start Time" modification buttons	P [Point]	1.1
Perceptual-Motor	Click on the "Start Time" modification buttons to enter correct time	B [Mouse]	0.1
Visual Search Working Memory	Locate appropriate "Site" selection	M [Locate]	1.2
Subgoal B: Modify personnel details			
Action: Enter personnel details			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Visual Search Working Memory	Locate the personnel details section	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to the "Me" button of personnel details	P [Point]	1.1
Perceptual-Motor	Click on the "Me" button of personnel details	B [Mouse]	0.1

Subgoal C: Save modified medication details			
Action: Select save button on “Drugs Administered” screen			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Working Memory	Determine if all medication details entered	M [Locate]	1.2
Visual Search Working Memory	Locate the “Next” button	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to “Next” button	P [Point]	1.1
Perceptual-Motor	Click on the “Next” button	B [Mouse]	0.1
System Response: Pop-up screen saves medication details and cycles to next medication			

5.5 Discussion

The navigational complexity framework has been employed to characterize differences in three different EHR systems. The overall ease of use and modes of interactions were generally simpler and required fewer perceptual-motor actions. Additionally, the fewer screen changes lessened the burden on working memory for users, thus reducing the overall cognitive load. Similarly, the clickstream data showed fewer mouse click activity between individual users and fewer dense clusters surrounding a specific part of the task. These insights were provided from the navigational complexity framework. From the user-based methods, the overall shorter occurrences of mouse clicks and goals from the cognitive walkthrough showed that the system facilitates clinicians to document single medications at a given time. In all three systems, there was a significant dependency on perceptual-motoric actions when navigating through the interface and locating the various fields for data entry, with specific emphasis being placed on SIS requiring a higher number of overall complexities in navigation. Through analyzing the steps executed to complete the MAR tasks, complexities in EHR navigation were identified across different systems and clinical settings. These complexities were reflected by multiple measures and were found to influence nurses' performances. These complexities surfaced through tradeoffs in cognitive processes that mediate task performance.

The focus of this validation is on EHR-mediated workflow and not exclusively on usability, although many methods common to usability studies were employed. Workflow is embedded in a more complicated process, spanning beyond basic task performance. Interface and system designs are informed in part by dependencies between tasks or be a result of the availability or absence of information collected at an earlier point in time. It is vital that the interface be understood in the context of other design choices and protocols driving the overall PreOp process. Differences in an interface can have rippling effects on workflow and affect task performance, specifically the time to complete a task. A better-designed interface can alleviate some of the burdens on working memory and thereby reduce the impact of the keyhole effect by enabling greater access to needed information on a given screen (54). The navigational framework proposed here can assist in illuminating the nature of the design decisions and inform future design solutions at a granular level that stretches beyond other methods and frameworks.

The combination of quantitative and qualitative data offers a method of precision and higher reproducibility. An additional advantage of the combination of methods and data is offering both precision and accuracy. The individual expert-based methods of KLM and cognitive walkthroughs offer a level of accuracy in that it can identify the ideal steps and ensure that users are following these steps. It also is accurate in illustrating users microstrategies compared to an ideal process. However, there is little precision in these methods. The user-based methods offer a higher level of precision in that there is consistency across users of a specific system and site, however there is a range of different measurements when compared to the ideal. By combining these two categories of methods, expert-based and expert-based, into a new analysis we can maximize precision and accuracy. This is done by aligning the user-based real-world processes with the expert-based ideal processes, and align the two to determine where users across a range of settings and systems fall when compared to a known ideal.

The clickstream analysis, coupled with the walkthrough, enables segmentation of the sequential task process and user experience at the micro-analytic level needed to surface challenges that users encounter and characterize them in a meaningful way. Using the proposed framework, I learned that the application of expert-based and user-based lead to meaningful characterizations of interface complexity by identifying complexities from the user standpoint and supporting the bottleneck with expert-based analysis when compared to user-based or expert-based methods alone. The single method approach only provides insight from a single standpoint, the user or the expert analysis. The combination of these methods, specifically in the modified walkthrough, aligns these interface viewpoints at a detailed level.

5.6 Conclusions

Navigational complexity has an impact on clinicians when leveraging the EHR during their daily work. In this chapter, the navigational complexity framework is applied to a single EHR-mediated workflow task to determine its viability and accuracy in prediction bottlenecks in system design that hinder workflow and burden users. The framework surfaces interactive behavior measures, supporting that different interfaces leveraged for task completion across systems mediate task performance. It is particularly useful for surfacing design tradeoffs that exist for users during interaction. With the tradeoffs identified, there can be evidenced-based small tractable changes that improve efficiency, streamline EHR-mediated workflow, and greatly enhance the user experience made.

The navigational complexity framework was applied in a microanalytic approach here on a single task to achieve two main goals: (1) to verify that all methodologies included in the framework are valid and provide useful results and (2) show the feasibility of applying the framework in real-world settings, beginning with a single task. This integrative methodological approach allows the interface to be analyzed from multiple aspects compared to the traditional single method in that it explores the dependencies users face with interface complexities and how microstrategies are used to optimize interaction and navigation. While this single task shows the success of the framework in identifying bottlenecks in workflow, it should be applied to additional, complex tasks that leverage different interfaces with different modes of interaction to ensure a full understanding of the complexities faced by clinicians using a variety of EHR interfaces and systems.

6 VALIDATION OF THE NAVIGATIONAL COMPLEXITY FRAMEWORK WITH A SINGLE EHR-MEDIATED WORKFLOW TASK: MEDICATION RECONCILIATION

6.1 Introduction

Medication reconciliation (MedRec) is considered a vital process across healthcare settings and has a particularly important role before surgery (10). MedRec is the process of comparing a record of a patient's currently prescribed medications with a list of medications the patient has actually been taking to ensure the record is current and accurate. Although the importance of the MedRec task is widely known, there is ample evidence to suggest that the systems currently implemented often provide inadequate cognitive support to clinicians, presenting significant usability challenges and barriers (7). Often when implementing a new EHR, medication discrepancies rate during MedRec near doubles (7). These discrepancies can largely be attributed to the interface design and the variation of use by clinicians, often facilitated by the system design. The poor usability of EHRs can contribute to the documentation burden problem that clinicians experience (60). Currently, few studies have compared the usability of various interfaces and systems with a collection of different types of analyses.

The navigational complexity framework was applied to the MedRec task to identify the navigational complexities in the interfaces when completing the task. This approach is similar to the approach taken with the MAR task in Chapter 4. Additionally, applying the framework to an additional task validates that the final selection of analyses can identify issues in interface design. Through this, we can provide evidence that the framework is valid for use during larger studies involving multiple systems, sites, settings, and tasks because it was previously validated with a range of tasks and systems. This chapter corresponds to Aim 2 of the thesis and presents the results by applying a section of analysis from the navigational complexity framework to the MedRec task. This was done to identify the cognitive tradeoffs and challenges involved in EHR-mediated task completion while refining the navigation complexity framework for in-situ use.

6.2 Methods

The framework has been applied to identify variations across clinical sites and individuals at these sites. The following two navigational complexity framework categories of analysis were applied to study navigational complexation in the MedRec task: expert-based and user-based methods. The expert-based methods (e.g., representational analysis) involve the evaluation and judgment of trained analysts. The user-based methods rely on empirical data derived typically from observational or experimental studies.

6.3 Clinical Settings

Observations for this phase of validation took place at two Mayo Clinic sites: Rochester containing two hospitals, Saint Marys and Methodist (Rochester, MN) Eau Claire Hospital (Eau Claire, WI), which is part of the Mayo Clinic Health System. In this report, the Methodist and Saint Marys campus are combined due to their similar processes and geographical location. Results from Eau Claire and Rochester campuses are presented. The analysis was performed on video capture of 18 different patient cases involving 11 nurses across all sites.

The primary focus of the data capture was on the PreOp nursing assessment performed by nursing staff in-situ on various patients. The Morae™ 3.3 video analytic software was used to capture the workflow, recording clinicians' on-screen activities. The software also provides a set of analytics and audio and video recordings of the clinicians' hands (e.g., using paper documents, checklists) via a webcam. During the data capture, an observer was also present to record notes and specific points of interest. The observer further employed a hand-held video camera and used it when permissible. Recordings were separated by patient cases across geographical locations. The patient case was the primary unit of analysis.

6.4 Data Analysis

Individual patient video recordings were reviewed for integrity and noticeable gaps in time (e.g., where no activity was observed), then were segmented into individual tasks based on an established clinical workflow task list. Once segmented, the specific task of interest was isolated, and data analysis was performed. As previously mentioned, the navigational complexity framework includes both expert-based and user-based analysis on the MedRec task (Figure 1). The expert-based methods included the representational analysis of interfaces to evaluate the appropriateness of representations for the given user performing a selected task and process modeling to represent the ideal sequence of steps involved in task completion. The user-based methods such as interactive behavior measures and individual clickstream data for each clinician were used to understand the actions users performed and to identify and explain variation across users, systems, and clinical sites. The tasks were coded sequentially, and once segmented specific analytics were generated from the videos. The analytics, interactive behavior measures were then converted to clickstream data, a timeline representation aiming to show variation and individual clicks involved with task completion. When tasks are sequentially coded, a visualization to show the fragmentation of tasks and task switching frequency within EHR-mediated workflow was generated. This enabled us to track multiple instances of tasks throughout PreOp.

6.5 Results

We compared the MedRec task for two different EHRs (MICS LastWord and Cerner PowerChart), and data were gathered from these two different systems. Figure 2 and Figure 3 show schematic representations of the individual interfaces used to complete the MedRec task. Figure 2 represents MICS LastWord and Cerner PowerChart. In the surgical setting, this process is particularly important. It ensures there are no reactions between the prescribed medications and anesthesia while also ensuring patients receive their prescribed medication during their hospital visit. The nurse caring for the patient completes the reconciliation process and the date and time of the last dose taken by the patient. The date, time, and if the medication is currently being taken are recorded.

6.5.1 User-Based Results: Task Interactive Behavior Measures

Table 10 presents the mean time and interactive behavior measures (mouse clicks and screen changes) for reconciling the last dose of a single medication dose. In Rochester, using MICS for MedRec, an average of 86 (47.96) seconds, 26.4 (14.60) mouse clicks, and 9.8 (14.60) screen changes were required to reconcile a single medication dose. This can largely be attributed to the interface design changes where all reconciliation functions were readily available on the interface, not requiring additional navigation. In Eau Claire, using Cerner PowerChart for MedRec, an average of 149 (51.5) seconds, 43 (30.0) mouse clicks, and 0.7 (1.2), screen changes were required pre-EHR conversion to reconcile a single medication. An overall reduction in time, mouse clicks, and screen changes was seen.

Table 10: Interactive Behavior Measures For MedRec - Eau Claire And Rochester

Mean (SD) of Time (sec)	**`Mean (SD) of Mouse Clicks**	**Mean (SD) of Screen Changes**	**Mean (SD) of Time (sec)**
Rochester (4/5)	26.4 (14.60)	9.8 (6.24)	86 (47.96)
Eau Claire (4/4)	43 (30.0)	0.7 (1.2)	149 (51.5)

6.5.2 User-Based Results: Task Clickstream Data

By modeling the individual users' clickstream data, the interaction complexities users' faces can be explored, showing the series of clicks required for task completion and overall task efficiency. User data visualization through clickstream has the primary goal of showing variation across individual users, systems, and clinical sites. Figure 5 reveals the clickstream data for Rochester and Eau Claire. The x-axis represents a timeline for MedRec, while each dot along the timeline represents a single click performed by the user associated with completing MedRec. Clusters indicate a high density of clicks, whereas segments of lines (i.e., periods) absent of clicks may reflect other activities such as visual search. In Rochester, findings show more overall clicks required with higher clusters of clicks overall using MICS LastWord. This is mainly facilitated by requiring users to select the desired medication then click multiple buttons to generate the pop-up screen for the last dose and saving details.

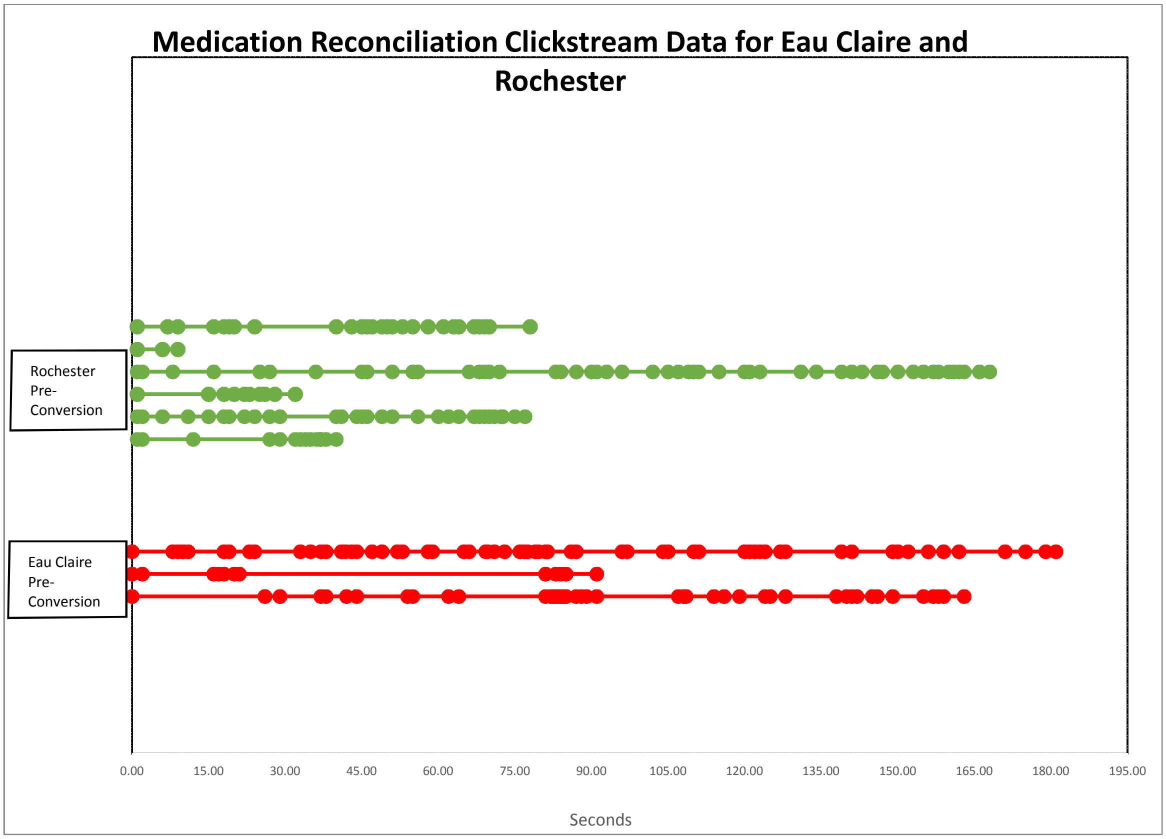


Figure 11: Clickstream Data Per User Of The MedRec Task.

6.5.3 Expert-Based Results: KLM

The KLM analytic method was performed on the set of operations required to complete the tasks of accessing the medication list and reconciling a single dose of a patient's medication. When comparing the observed and KLM measures for the entire MedRec task, there are some interesting differences across different clinical sites leveraging different clinical systems (Table 5). This allows for quantifying complex interactions in more precise terms. While Eau Claire and Rochester utilize different systems, different user steps for navigation and task completion are required.

Table 5 shows KLM estimates and measures of interactive behavior collected from direct observation for MedRec. The estimates and actual times provided enable for accessing the MedRec interface and reconciling a single medication. The KLM for a single medication is higher in Rochester (15.6 seconds) than Eau Claire (12.8 seconds) in Eau Claire. Rochester required an average time of 12.05, while Eau Claire requires 10.86 seconds. The KLM estimate accurately predicted the completion time, although we only had a small number of observations for testing the model. Both the KLM prediction and the observed (user) time measurements estimated that Eau Claire took less time than Rochester to complete MedRec.

Table 11: KLM Estimates And Actual Times For Medrec - Rochester And Eau Claire

Task completed/ All cases)	Mean Total (SD) of Time	Time Per Single Medication (SD)	KLM Per Single Medication
Rochester (4/4)	106 (114)	12.05 (1.91)	15.6
Eau Claire (4/4)	97 (39)	10.86 (1.0)	12.8

6.5.4 Expert-based Methods: CW

A cognitive walkthrough for the MedRec task was performed for both SurgiNet/PowerChart and LastWord. These can be seen in Tables 9 and 10. The analysis showed that the MedRec tasks generally require the same amount of work to complete. Both sites required 3 sub-goals to complete the main task, but there were differences in the process. In Eau Claire, the functions to support a range of activities that facilitate the reconciliation of the last medication dose are not visible on the main screen. The nurse must select the medication and right-click on it to see the range of options. In Rochester, there is a section at the bottom of the screen with various utilities that can be applied to the medication. The difference in actions adds up over the course of multiple medications. In Eau Claire, the medication verification process is more streamlined. On the other hand, more information was gathered regarding the person (e.g., nurse or pharmacist) completing the verification process.

Table 12: MedRec Cognitive Walkthrough - Rochester

Goal: Complete medication reconciliation
Start State **Screen**: Enterprise Order Prescribing Home Screen **Subgoal:** Find current medication list **Action**: Enter shorthand code **System Response**: full medication list displayed on new screen **Subgoal**: Reconcile medications **Action**: Select medication **System Response**: System highlights medication to distinguish from list **Action**: Click on “Add Dose Last Taken” button **System Response**: Pop-up window opens with auto-populated current date and time **Action:** Nurse adjusts time based off of patient response and saves **System Response:** Date and time entered saved under “Dose last Taken” column **Subgoal:** Verify medications **Action:** Nurse clicks to apply verification message **System Response:** Pop-up window with dropdown menus for verification information opens **Action:** Nurse enters appropriate information and saves **System Response:** System saves message and marks medication list as reviewed

Table 13: MedRec Cognitive Walkthrough – Eau Claire

Goal: Complete medication reconciliation Start State **Screen**: SurgiNet IView screen **Subgoal:** Find current medication list

Action: Navigate to Orders section
System Response: Screen transitions to page with all orders listed
Action: Click "Document Medication by Hx" tab
System Response: List of current medications is displayed
Subgoal: Reconcile medications
Action: Select medication
System Response: System highlights medication to distinguish from list
Action: Right click on medication and choose "Add Compliance" option
System Response: Bottom of screen shifts to show details for medication
Action: Nurse adjusts time of last dose based off of patient response and saves
System Response: Date and time entered are saved
Subgoal: Verify medications
Action: Nurse clicks "Document History" button
System Response: System saves reconciled medication list

6.5.5 Expert-based Methods: Representational Analysis

For the currently implemented EHRs, the information documented is relatively uniform between the sites and systems; however, the mode of interactions between the systems varies considerably. These interactive differences can be seen in the steps required to enter the last dosage of a medication. Figure 5 and Figure 6 present a schematic representation of the interfaces used for MedRec. During the preoperative nursing assessment, current at-home medications were documented by the nurse completing the assessment. Typically, the date and time of the last medication dose were recorded. The information collected regarding each medication was standard across nurses, whereas the process of accessing the medication list and the compliance section were different. MedRec involves the same set of functions in the two systems; however, the steps to access the medication list and add the last dose differ.

In Rochester, a medication list was displayed on the screen, and the "Add Last Dose Taken" button was selected to add the last medication dose, generating a pop-up screen to enter the date and time of the dose. The last date and time are entered, the "Continue" button was selected, and the entry was saved, closing the pop-up screen. This required clinicians to utilize their working memory to recall what medication dose was being entered, given that the pop-up window covers the medication list. However, less visual was search required by engaging a pop-up window with the specific purpose of entering date/time. In Eau Claire, a similar process for entering the medication's last doses occurred. A medication list was displayed, and the desired medication was selected. The user right-clicks and selects "Add Last Medication Dose". Once selected, the screen split into two different sections, showing the medication list and the compliance section where the last medication date and times were entered. This interface design required more perceptual-motor activity but placed less of an overall burden on working memory than Rochester because the medication list was easily and readily visible.

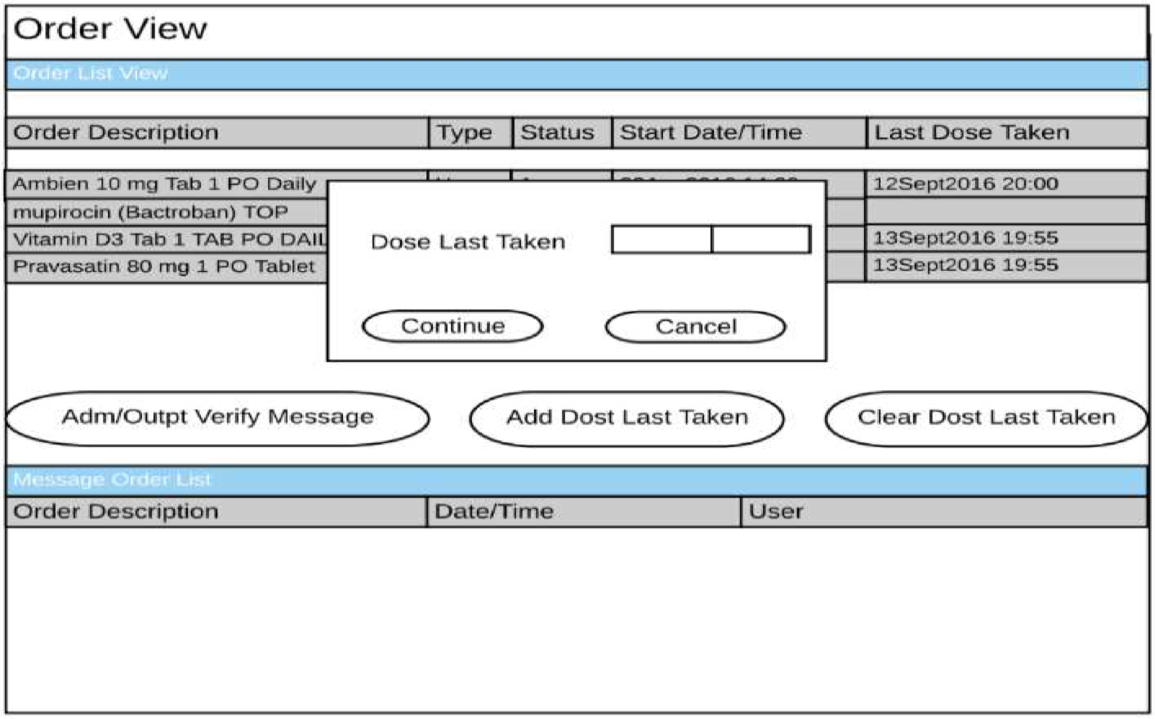


Figure 12: Schematic Representation Of MedRec Interface - Rochester

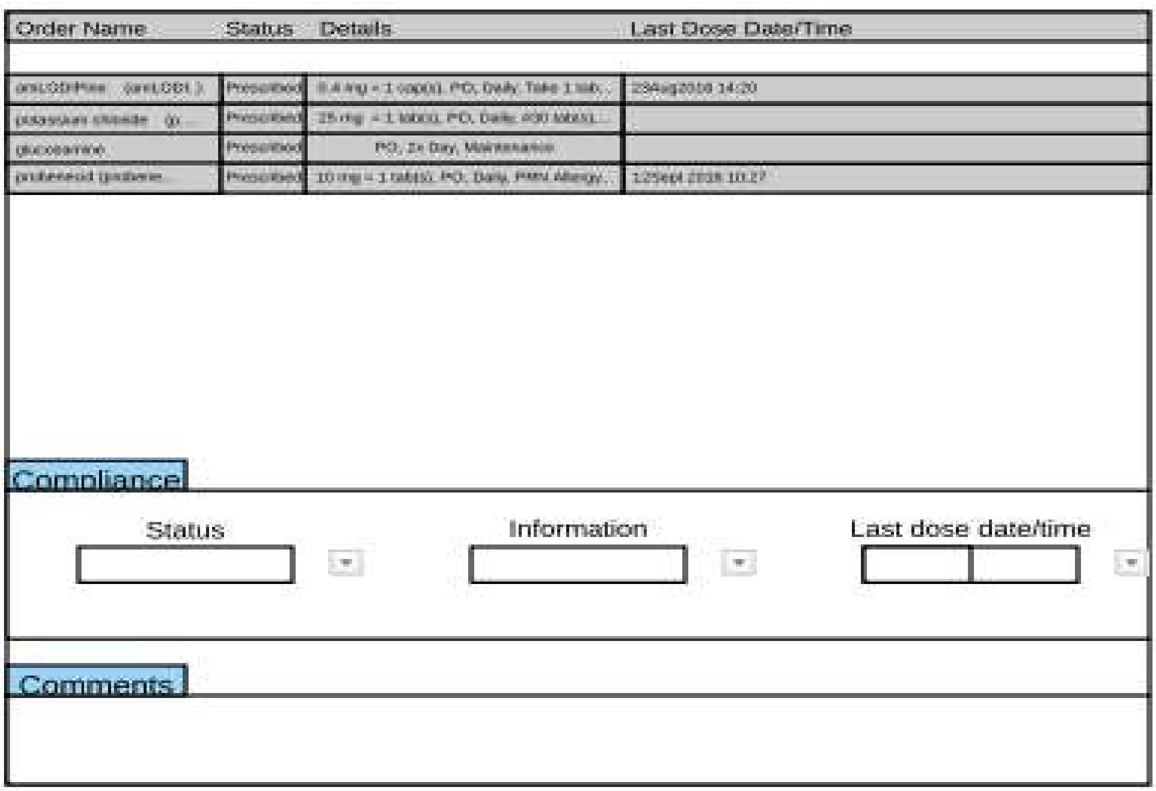


Figure 13: Schematic Representation Of Medrec Interface – Eau Claire

6.5.6 Combination Method: Cognitive Walkthrough/KLM Combination

Table 6 presents a sample of the cognitive walkthrough/KLM combination, showing goals, subgoals, and actions associated with a task (MedRec in this case). The analysis included a description of the sequential process or flow, actions involved, the time it took to complete this part of the task, and characterization of the demands on cognitive processes. Analysis was completed by aligning the expert-based cognitive walkthrough goals and subgoals, KLM actions and estimated action times, and user-based cognitive processes. These results were coordinated with the RA results, with interface representations highlighting specific design elements and representations of information. These results indicated that the tasks are realized in different ways across the systems. During the categorization of constructs, it was discovered that there is high visual search to locate specific pieces of information on the interface due to high number of menu choices. However, there is relatively equal amounts of working memory and perceptual-motor actions required for interaction. There is a total of twelve occurrences of visual search, seven occurrences of working memory and ten occurrences of perceptual-motor actions in Eau Claire. In Rochester, there are twelve occurrences of visual search, three occurrences of working memory and seventeen occurrences of perceptual-motor actions. Table 14 and Table 15 illustrate the integrative methodological approach.

Table 14: Cognitive Walkthrough And KLM Combination For Eau Claire

Cognitive Process	**Description**	**Operation**	**Time (sec)**

Goal 1: Navigate to MedRec Screen			
Subgoal A: Locate "Document Medication by Hx" button			
Action: Search screen for the “Document Medication by Hx” button			
Cognitive Process	***Description***	***Operation***	***Time (Sec)***
Visual Search Working Memory	Locate "Document Medication by Hx” button	M [Locate]	1.2
Subgoal B: Select "Document Medication by Hx" button			
Action: Click on "Document Medication by Hx" button under Menu Options			
Cognitive Process	**Description**	**Operation**	**Time (Sec)**
Perceptual-Motor Visual Search	Point to "Document Medication by Hx" button	P [Point]	1.1
Perceptual-Motor	Click on "Document Medication by Hx" button	B [Mouse]	0.1
System Response: List of Current Medications is Displayed			
Goal 2: Document Last Medication Dose			
Subgoal A: Locate the desired medication			
Action: Search medication list for desired medication			
Cognitive Process	**Description**	**Operation**	**Time (Sec)**
Visual Search Working Memory	Locate the desired medication	M [Locate]	1.2
Subgoal B: Select the desired medication			
Action: Click on the desired medication			
Perceptual-Motor Visual Search	Point to desired medication	P [Point]	1.1
Perceptual-Motor	Click on desired medication	B [Mouse]	0.1
Subgoal C: Locate the "Add Compliance" Menu Choice			
Action: Search for "Add Compliance" Menu Choice			
Cognitive Process	**Description**	**Operation**	**Time (Sec)**
Visual Search		M [Locate]	1.2

Working Memory	Locate "Add Compliance" Menu Choice		
Action: Click on "Add Compliance" Menu Choice			
Cognitive Process	**Description**	**Operation**	**Time (Sec)**
Perceptual-Motor Visual Search	Point to "Add Compliance" Menu Choice	P [Point]	1.1
Perceptual-Motor	Click on "Add Compliance" Menu Choice	B [Mouse]	0.1
Subgoal D: Log last medication dose			
Action: Enter last medication date/time into system			
Cognitive Process	**Description**	**Operation**	**Time (Sec)**
Working Memory	Determine the last date/time of medication taken	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to last dose date/time window	P [Point]	1.1
Perceptual-Motor	Click on last dose date/time window	B [Mouse]	0.1
Perceptual-Motor Visual Search	Point to appropriate date in calendar	P [Point]	1.1
Perceptual-Motor	Click on appropriate date in calendar	B [Mouse]	0.1
Perceptual-Motor Visual Search	Point to "Time" box	P [Point]	1.1
Perceptual-Motor	Click on "Time" box	B [Mouse]	0.1
Perceptual-Motor Visual Search	Type appropriate time	K [Numbers]	0.8

Table 15: Cognitive Walkthrough And KLM Combination For Rochester

Goal 1: Navigate to MedRec Screen		
Subgoal A: Locate "Medications" button from dropdown menu		

Action: Search screen for the "Medications" button from dropdown menu			
Cognitive Process	**Description**	**Operation**	**Time (Sec)**
Visual Search Working Memory	Locate "Medications" button from dropdown menu	M [Locate]	1.2
Subgoal B: Enter shorthand code for medication list			
Action: Type shorthand code for medication list into textbox			
Perceptual-Motor Visual Search	Point to "Medications" button from dropdown menu	P [Point]	1.1
Perceptual-Motor	Click on "Medications" button from dropdown menu	B [Mouse]	0.1
Action: Type shorthand code for medication list into textbox			
Cognitive Process	**Description**	**Description**	**Operation**
Perceptual-Motor Visual Search	Type appropriate shorthand code	K [Numbers]	1.6
Perceptual-Motor Visual Search	Point to "Continue" button	P [Point]	1.1
Perceptual-Motor	Click on "Continue" button	B [Mouse]	0.1
System Response: List of Current Medications is Displayed			
Perceptual-Motor Visual Search	Point to "Message" button	P [Point]	1.1
Perceptual-Motor	Click on "Message" button	B [Mouse]	0.1
System Response: MedRec last dose pop-up window generated			
Goal 2: Document Last Medication Dose			
Subgoal A: Locate the desired medication			
Action: Search medication list for desired medication			
Cognitive Process	**Description**	**Operation**	**Time (Sec)**

Visual Search Working Memory	Locate the desired medication	M [Locate]	1.2
Subgoal B: Select the desired medication			
Action: Click on the desired medication			
Perceptual-Motor Visual Search	Point to desired medication	P [Point]	1.1
Perceptual-Motor	Click on desired medication	B [Mouse]	0.1
Subgoal C: Locate the "Add Last Dose Taken" button			
Action: Click on "Add Compliance" Menu Choice			
Cognitive Process	**Description**	**Operation**	**Time (Sec)**
Perceptual-Motor Visual Search	Point to Add Last Dose Taken" button	P [Point]	1.1
Perceptual-Motor	Click on Add Last Dose Taken" button	B [Mouse]	0.1
Subgoal D: Log last medication dose			
Action: Enter last medication date/time into system			
Cognitive Process	**Description**	**Operation**	**Time (Sec)**
Working Memory	Determine the last date/time of medication taken	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to last dose date/time window	P [Point]	1.1
Perceptual-Motor	Click on last dose date/time window	B [Mouse]	0.1
System Response: Calendar is shown in pop-up window			
Perceptual-Motor Visual Search	Point to appropriate date in calendar	P [Point]	1.1
Perceptual-Motor	Click on appropriate date in calendar	B [Mouse]	0.1
Perceptual-Motor Visual Search	Point to "Time" box	P [Point]	1.1
Perceptual-Motor	Click on "Time" box	B [Mouse]	0.1
Perceptual-Motor Visual Search	Type appropriate time	K [Numbers]	0.8

System Response: Date/time entered for medication are saved in pop-up window

6.6 Discussion

Shorter mean duration, fewer mouse clicks, and screen changes per medication were observed using the proposed framework during the MedRec task overall. When comparing the systems, the MedRec interface's ease of access and modes of interactions were generally simpler and required fewer perceptual-motor actions in Rochester's interface. Further, fewer screen changes lessened the burden on working memory for users, reducing the overall cognitive load. This was also evidenced in the clickstream data, showing fewer mouse clicks activity of individual users and fewer dense clusters surrounding a specific part of the task. In the context of the nurses' work, the most recent home medication list was reviewed with the patient, and the patient provides the last time the medication was taken. However, in Eau Claire, the compliance section was not readily available, requiring additional navigation and burdening the working memory of the nurses to entering the medication details. Conversely, a more complicated case than observed in the study may result in greater visual search.

This phase of the framework validation documented changes to the EHR-mediated workflow as reflected in measures of interactive behavior. There are currently substantial challenges for comparing EHRs (57) and few frameworks to inform the usability comparison (33), resulting in a lack of information to guide new EHR selection decision-making. This work aimed to contrast the EHR-mediated workflow and how interface design can affect navigational complexity and task efficiency. The process of MedRec across three tertiary charting systems was compared through the application of the navigational complexity framework. Differences were observed in the modes of interaction as mediated by small differences in interface design. However, a growing body of research has expanded the range of usability research and situated it within the broader spectrum of EHR-mediated workflow. Recent efforts have been made to characterize, operationalize, and reduce navigational complexity.

Applying the framework to two significantly different tasks across multiple systems has determined the best combination of user-based and expert-based methods. The final step of validating the framework is applying it to a more complex situation (i.e., pre- and post-implementation of an EHR) to determine its feasibility and overall applicability during a new system's implementation. This will further validate if the framework can identify usability issues in lateral systems (systems used concurrently) and the transition of systems for overall workflow improvements. The framework should be a supporting tool in determining which systems are optimized for EHR-mediated workflow.

6.7 Conclusions

With the application of the navigational complexity framework to two individual tasks, leveraging different interfaces across different systems, the selected collection of user-based and expert-based methods can identify issues in interface design and navigation burdens. This single task approach proves that the framework can assist in understanding task complexities at a granular level. However, the clinical workflow does not consist of a single task across a single system. The single-task validation evidences the framework as executable and feasible. However, it does not yet verify that it is an effective tool for system comparison between pre- and post-implementation of new EHR systems. Further verification testing to determine the extent to which the framework can identify barriers is presented in the next chapter across a pre- and post-implementation.

7 EXTENSION OF NAVIGATIONAL COMPLEXITY FRAMEWORK TO A PRE/POST-EHR IMPLEMENTATION FOR EVALUATION OF FRAMEWORK ACCURACY: PATIENT ORDER MANAGEMENT

7.1 Introduction

In this chapter, the proposed navigational framework is applied to identifying the complexities in navigation variations across clinical sites and individuals. In Chapter 4 and Chapter 5, the framework was applied to one task at a time to determine the optimal combination of methods for identifying problems in usability. Compared to the initial validation phase of individual tasks, this chapter's goal is to determine the feasibility and applicability of the framework in a pre/post-EHR implementation setting.

There is little understanding of the effect of new EHR implementation on clinician productivity (91). When adopting these new systems, there is a fear of loss of productivity from poor usability and system design. One of the main issues cited is to prepare users by identifying previously existing issues in the legacy system and ensure these bottlenecks are remedied in the new system through in-situ use to minimize productivity loss from system usability. While the benefits of EHRs are nearly endless for patient care and safety, implementing a new system can often carry unforeseen consequences, many of which are carried over from the legacy system. By studying system use pre-implementation, current bottlenecks in system use the clinical workflow can be identified and analyzed in detail to propose a solution in the newly implemented system and workflow. These bottlenecks changes can then be studied post-implementation to determine if there were true efficiency changes.

With an increasing rate of EHR conversions to different systems, there has been a discernible impact on the workflow associated with the system (the EHR-mediated workflow). Often, little attention is paid to comparing the legacy EHR to the newly implemented EHR, and there are even fewer frameworks that inform usability comparisons of these systems. Comparing EHRs pre/post-implementation has received little attention from researchers, even though it is recognized as a time of risk concerning the direct impact of new system implementation on usability and safety (71). EHR usability and safety can be optimized overall by comparing systems pre- and post-implementation, enabling them to reach their full potential. The comparisons completed have often involved a single comparison method that lacks providing an in-depth understanding of existing issues in the legacy system. Wijesinghe et al. (92) completed an evaluation of the extent to which the existing usability evaluation models can accurately and effectively depict usability issues. When leveraging a single method (e.g., a cognitive walkthrough), it failed to fully identify problems besides issues based on user tasks, such as poor visibility.

Providers often perceive EHRs as challenging to use, and usability analysts have cited issues with difficult-to-read interfaces, confusing displays, and iconography lacking consistency and intuitive meaning (26). These usability issues can often lead to an increased cognitive load. These challenges may surface when enterprises transition from a legacy system or interface to another, causing disruptions to workflows and efficiency (51, 52). By applying the navigational complexity framework, we can gain insight into how different EHR interfaces differentially mediate task performance and document changes after system implementation. This also allows for a deeper understanding of task complexities at a granular level.

7.2 Settings

During the pre- and post-implementation of the EHR, observations took place at four Mayo Clinic hospitals in Phoenix, AZ, Rochester, MN (including St. Marys and Methodist hospitals), Jacksonville, FL, and Eau Claire, WI. The analysis was performed by video capturing 18 different patient cases involving 11 nurses across all sites. A total of 14 hours of video recordings were captured across 11 different nurses over ten days at the three different clinical sites, which are presented in this work. The primary focus of the data capture was on the PreOp nursing assessment performed by nursing staff in-situ on various patients. Morae™ 3.3 video analytic software was used to capture the workflow, where the software recorded the clinician's on-screen activities. Notably, the pre-implementation and post-implementation sites differed due to conflicts in data collection. However, these sites are presented for post-implementation data because the new EHR is being implemented across all sites with identical processes.

7.3 Data Analysis

Video recordings of individual patient encounters were reviewed for integrity and noticeable gaps in time. Following this, they were segmented into different tasks based on an established clinical workflow task list. Once segmented, the specific task of interest was isolated. The applied navigational complexity framework included expert-based and user-based analyses on the patient order management (POM) task. The expert-based methods included representational analysis of interfaces to evaluate the appropriateness of representations for performing a selected task and process modeling to represent the ideal sequence of steps involved in task completion. The user-based methods, such as interactive behavior measures, for each clinician were used to understand what actions users performed and identify and explain variations across users, systems, and clinical sites. Functional analysis was performed to gain a thorough understanding of the functionalities required to meet specific work requirements (33). User interface elements were categorized as objects or operations and situated within the task completion, where each function was utilized.

7.4 Results

The POM task compared two different systems: System 1 (the legacy system) and the newly implemented Epic system. Schematic representations of the interfaces used for POM in System 1 and Epic are presented in Figure 1 and Figure 2. In the surgical setting, this is a particularly important task, given that no processes involving patient care can be completed unless an order is entered for that process. The method of managing patient orders includes activating and deactivating orders for execution, releasing orders from holding for various clinical tasks, and creating verbal orders for emerging tasks for specific patients that must be completed. The results are organized as follows: (1) interactive behaviors executed during the POM task, (2) clickstream visualization to show user activity, (3) KLM comparing the ideal to actual task completion times, (4) schematic representations of the interfaces used in POM to visualize the interface elements and (5) the cognitive walkthrough/KLM to show the goals, actions, and cognitive processes of task completion.

7.4.1 User-Based Results: Task Interactive Behavior Measures

Table 8 and Table 9 represent the different interactive behavior measures (mouse clicks, screen changes) required by a user when completing the POM task in the pre-implementation system across various clinical sites, all using the same system. These measures show the average values across users. These measurements provide insight into the effort required by users to complete a task and task performance to quantify better the burden of navigational complexity placed on clinicians. The functionalities and navigation were nearly identical; only the presentation of data varied.

Table 16: Interactive Behavior Measures For POM – Pre-Implementation

Location (Task completed/ All cases)	**Mean (SD) of Time (sec)**	**Mean (SD) of Mouse Clicks**	**Mean (SD) of Screen Changes**
Arizona (6/8)	198 (138)	61.4 (47.72)	18.6 (11.9)
Florida (4/7)	98 (59)	12.67 (13.67)	9.00 (8.49)
Eau Claire (3/3)	36 (29)	7.0 (5.1)	4.5 (3.0)

Table 17: Interactive Behavior Measures For POM - Epic

Location (Task completed/ All cases)	**Mean (SD) of Time (sec)**	**Mean (SD) of Mouse Clicks**	**Mean (SD) of Screen Changes**
Eau Claire (3/3)	46.25 (49.72)	6.75 (3.63)	3.5 (1.65)
St. Marys (5/5)	35.8 (14.4)	9.33 (3.2)	5.3 (2.0)
Methodist (4/5)	28.02 (5.24)	6.2 (2.6)	2.2 (1.37)

7.4.2 User-Based Results: Task Clickstream Data

Clickstream data were collected for individual users and modeled on a timeline, showing the series of clicks throughout task completion to explore how different interface designs exist during the pre- and post-implementations of new EHR systems. Results are shown in Figure 7 and Figure 8, showing clickstream data for Arizona (blue), Florida (red), and Eau Claire (green). There were six cases of POM in Arizona, four in Florida, and three in Eau Claire. Arizona generally required more time to complete the task with more complexity, as seen by the increased clicks relative to Eau Claire and Florida. The large clusters of clicks seen typically towards the end of each Arizona case represent the extra steps required to complete the task shown in Table 1. Although only four extra steps are shown, these steps must be completed for each individual patient order, resulting in a higher frequency of clicks at the end of each case. In contrast, Florida and Eau Claire had a simpler workflow overall.

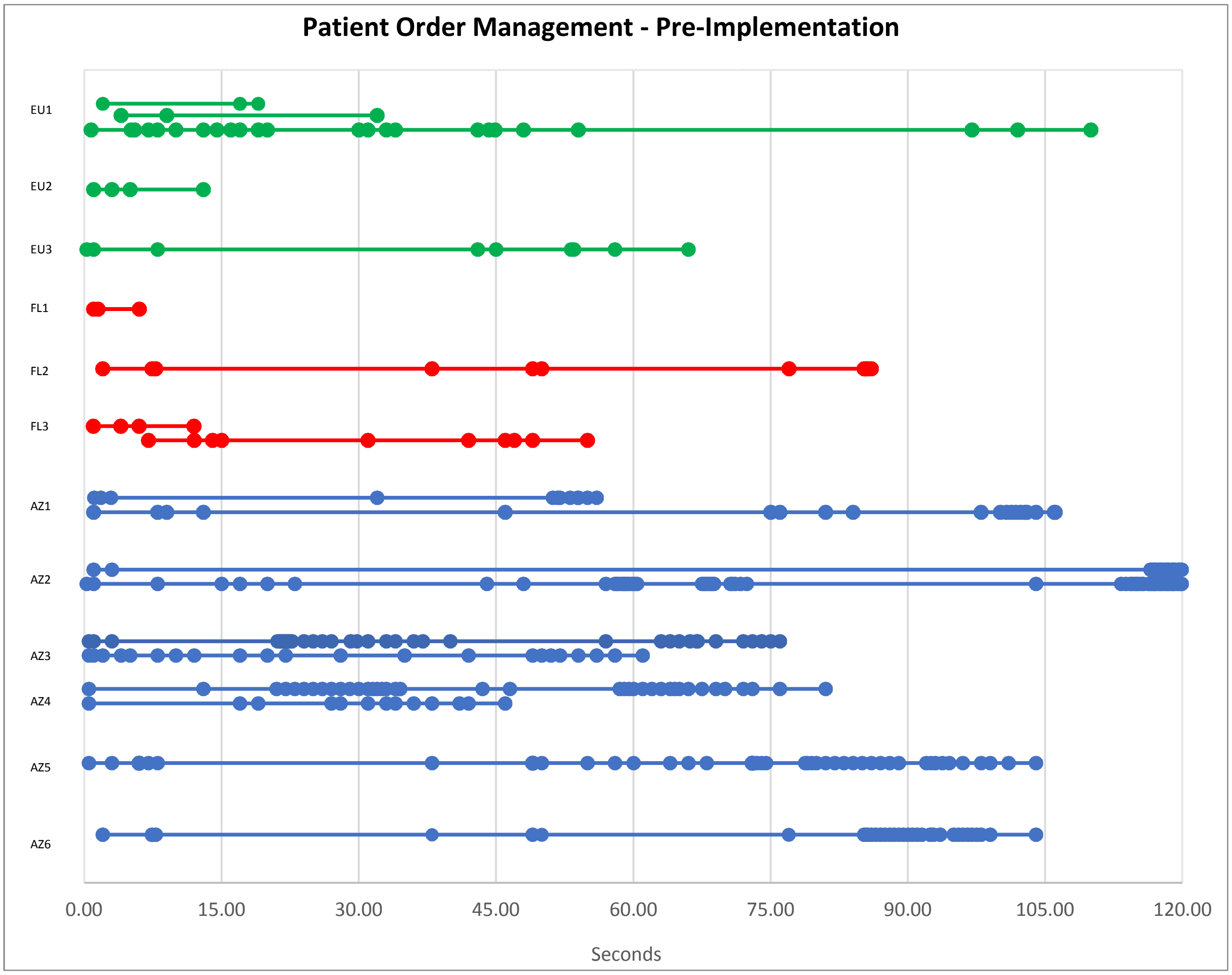


Figure 14: Clickstream Data Per User Of The POM Task Pre-Implementation

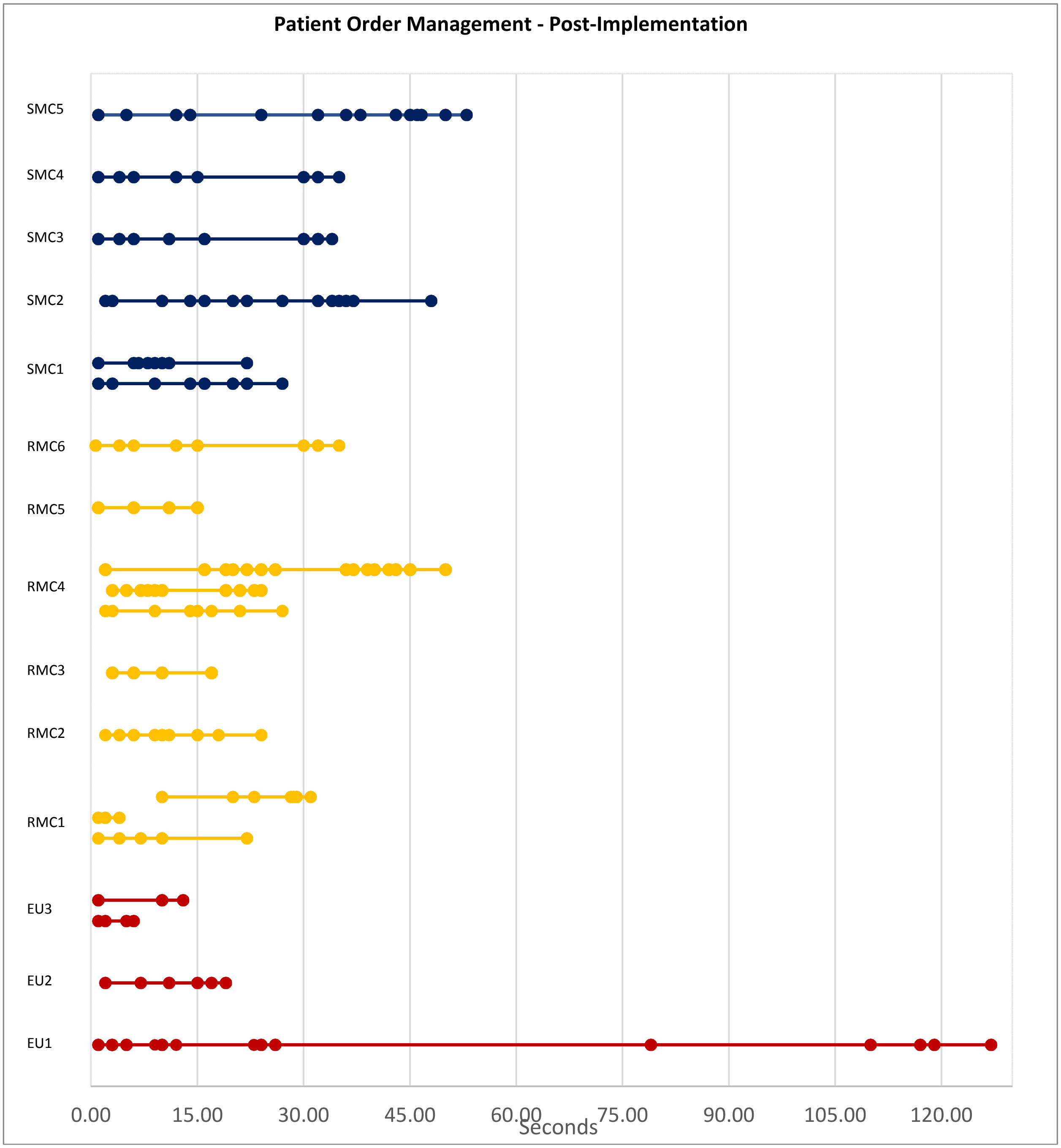


Figure 15: Clickstream Data Per User Of The POM Task Post-Implementation

7.4.3 Expert-Based Results: KLM

Interesting differences were observed when comparing the observed and KLM measures for the entire MAR task, as shown in Table 10 and Table 11. In Florida, nearly one-fifth of the observed time was spent waiting for the system to load and populate the screen with patient information, accounting for the difference between the observed and KLM measures. The KLM estimates ranged from 20.4 seconds for Arizona to 16.8 seconds for Florida and Eau Claire. Epic presented a significantly smaller number of available functions when accessing the POM interface. While different sites were presented for Epic, the practices executed by clinicians were identical enterprise-wide, allowing for generalizations of the estimates for task completion across these sites. Epic was most consistent with KLM estimates at 9.6 seconds for all sites, with little variation in the actual time to complete a task. Eau Claire and Methodist took 11.22 seconds and 11.33 seconds to complete, respectively, while Saint Marys took 11.72 seconds.

Table 18: KLM Estimates And Actual Times For POM – Pre-Implementation

Task completed/ All cases)	Mean (SD) of Time (sec)	Actual Time (sec)	KLM (sec)
Eau Claire	36 (29)	15.61	16.8
Arizona	198 (138)	20.1	20.4
Florida	98 (59)	23.57	16.8

Table 19: KLM Estimates And Actual Times For POM – Epic

Task completed/ All cases)	Mean (SD) of Time (sec)	Actual Time (sec)	KLM (sec)
Eau Claire	46.25 (49.72)	11.22	9.6

St. Marys	35.8 (14.4)	11.72	9.6
Methodist	28.02 (5.24)	11.3	9.6

7.4.4 Expert-Based Results: CW

In order to efficiently interact with the functions on-screen to complete the task, clinicians need to situate the process as goals and subgoals with associated actions and system responses based on user actions. While there are physical actions (mouse clicks), these do not show the complexities involved with task completion. To understand these complexities and how functions influence the cognitive processes, a CW was performed to show the goal, actions and system responses that occur when completing the POM task as seen in Tables 20 and 21. The goal of this analysis was to use the cognitive walkthrough to show the milestones of task progress and detail the physical actions taken by users to reach task milestones and goals used during task completion. Table 20 shows a portion of a main goal, subgoals, user actions and system responses associated with POM for the pre-implementation system. Being that the processes are largely identical for all sites, this table reflects the general process with slight variations existing for site specific details. The primary goal of all systems was to navigate to the appropriate interface and activate appropriate patient orders. Table 21 shows the CW for the post-implementation system, Epic. Only one CW exists for these sites and the same system with identical interfaces was utilized.

Table 20: POM Cognitive Walkthrough - Pre-Implementation

Goal: Activate and Release Patient Orders
Start State

Screen: Enterprise Order Prescribing Home Screen
Subgoal: Navigate to "Orders" page
    Action: Click on "Orders-Charges" Tab under Menu Options
    System Response: Generates "Orders" Screen
    Action: Click on "Signed and Held" section
    System Response: Filters orders to be released
    Action: Click on "SURG General PreOp orders"
    System Response: Filters orders to only PreOp orders
Subgoal: Activate and release orders
    Action: Click Orders to Activate
    System Response: Activated list of orders for review
    Action: Click on "Release" button
    System Response: Orders release for activation
    Action: Click on "Activate" button
    System Response: Orders activated to be executed

Table 21: POM Cognitive Walkthrough - Epic

Goal: Activate and Release Patient Orders

Start State
Screen: Epic Patient Summary Page
Subgoal: Navigate to "Orders" page
    Action: Click on "SURG General PreOp orders"
    System Response: Filters orders to only PreOp orders
Subgoal: Activate and release orders
    Action: Select Orders to Activate
    System Response: Activated list of orders for review
    Action: Click on "Activate" button
    System Response: Orders activated to be executed

7.4.5 Expert-Based Results: Representational Analysis

Figure 9 and Figure 10 present schematic representations of individual interfaces used to complete the POM task. There is a general universal protocol for releasing and activating orders across all surgical settings. However, the process in which these steps are completed varies substantially across systems. Information relating to POM was displayed in a list form, with the ability to shift between various sections of orders through a navigation pane. Although the steps involved in task completion were nearly identical, there are differences in the representations of orders, the headers used to categorize orders in particular. In Epic, there is an overall smaller subset of functions available to users within the interface for activating orders. By restricting the displayed functions, there is a more streamlined workflow that makes the overall process simpler but at the expense of not having proximal access to other desired functions

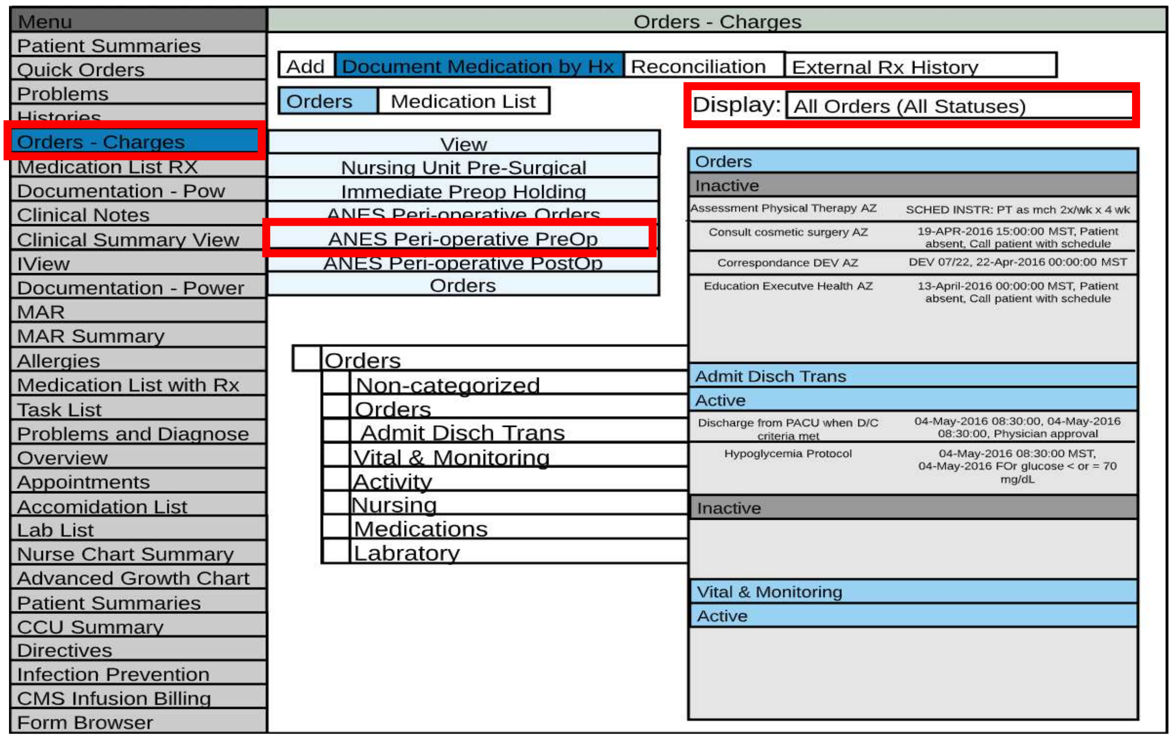
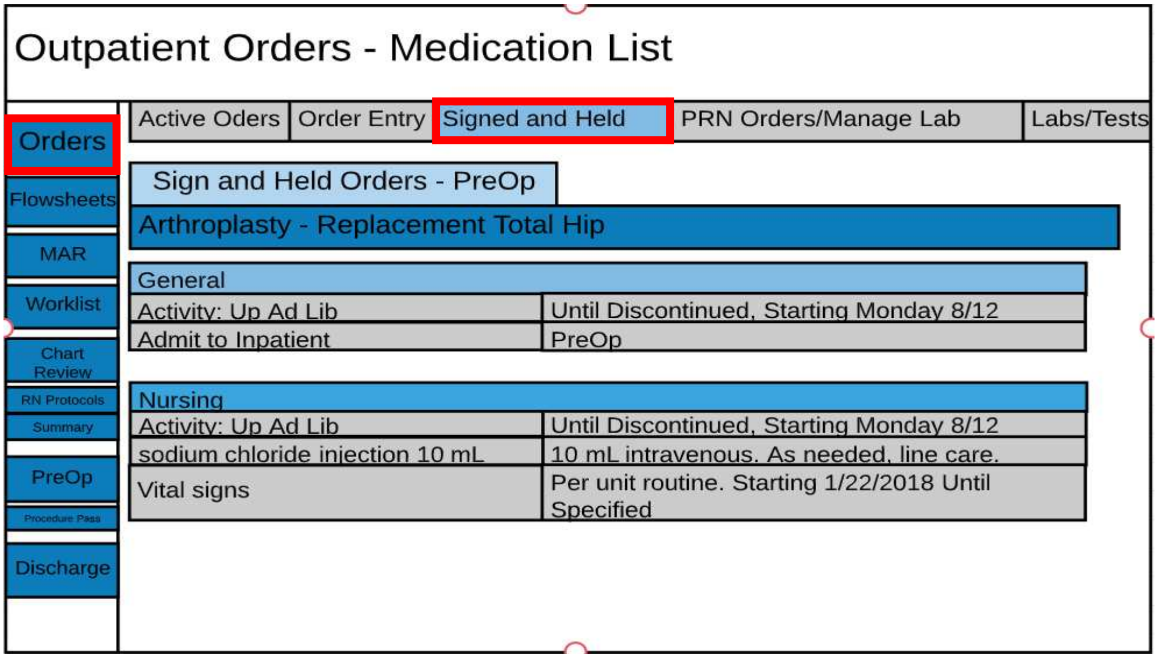


Figure 16: POM Schematic Representation Pre-Conversion

Figure 17: POM Schematic Representation Post-Conversion



7.4.6 Combination Method: Cognitive Walkthrough/KLM Combination

Clinicians must situate the patient order management process as goals and subgoals with associated actions and cognitive processes to interact with the functions on-screen to complete the task efficiently. While there are physical actions (mouse clicks), these cannot reveal the complexities involved with task completion. A sample of the combination KLM/cognitive walkthrough for the pre-implementation system and Epic is shown in Table 22 and Table 23. This analysis's purpose was to use the cognitive walkthrough to show the task progress milestones and then leverage the KLM to model the users' physical and mental actions to reach these milestones.

In the pre-implementation workflow, there is a high occurrence of perceptual-motor actions and visual search to complete a subgoal while low working memory was required. There is a total of nine occurrences of visual search, five occurrences of working memory and ten occurrences of perceptual-motor actions. When compared to the post-implementation system, there are equal amounts of all three cognitive constructs meaning there are equal number of tradeoffs. Although there are equal tradeoffs, there is a high overall occurrence of the constructs. There is a total of seven occurrences of visual search, six occurrences of working memory and 6 occurrences of perceptual-motor actions.

Table 22: Combination KLM and CW for POM - Pre-implementation

Goal 2: Activate Appropriate Order sets			
Subgoal A: Locate Appropriate Section of Orders			
Action: Search Header options for the "Signed and Held" section			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Working Memory	Decide what order section is appropriate	M [Locate]	1.2
Visual Search Working Memory	Locate the "Signed and Held" section	M [Locate]	1.2
Subgoal B: Select "Signed and Held" section			
Action: Click on "Signed and Held" section			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Perceptual-Motor Visual Search	Point to "Signed and Held" section	P [Point]	1.1
Perceptual-Motor	Click on "Signed and Held" section	B [Mouse]	0.1
System Response: Show all Orders in section			
Subgoal C: Determine Appropriate Orders for Patient			
Action: Select appropriate order sets to release			
Cognitive Process	Description	Operation	*Time (Sec)*
Visual Search Working Memory	Locate the order sets to release	M [Locate]	1.2

Perceptual-Motor Visual Search	Point to the checkbox of the order set to release	P [Point]	1.1
Perceptual-Motor	Click on the checkbox of the order set to release	B [Mouse]	0.1
Perceptual-Motor Visual Search	Point to the "Release" button	P [Point]	1.1
Perceptual-Motor	Click on the "Release" button	B [Mouse]	0.1
System Response: Ordered released to be executed			
Subgoal D: Activate Appropriate Orders			
Action: Select Orders to Activate			
Cognitive Process	Description	Operation	Time (Sec)
Visual Search Working Memory	Locate the orders order section to activate	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to order section to activate	P [Point]	1.1
Perceptual-Motor	Click on order section to activate	B [Mouse]	0.1
Visual Search Working Memory	Locate "Activate" button	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to "Activate" button	P [Point]	1.1
Perceptual-Motor	Click on "Activate" button	B [Mouse]	0.1
System Response: Activated list of orders for review			

Table 23: Combination KLM and CW for POM - Epic

Goal 2: Activate Appropriate Orders			
Subgoal A: Locate Appropriate Section of Orders			
Action: Search Header options for the "SURG General PreOp AZ" Section			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Working Memory	Decide what order section is appropriate	M [Locate]	1.2
Visual Search Working Memory	Locate the "SURG General PreOp AZ" section	M [Locate]	1.2
Subgoal B: Select "SURG General PreOp AZ" Section			
Action: Click on "SURG General PreOp AZ" Header			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*

Perceptual-Motor Visual Search	Point to "SURG General PreOp AZ" section	P [Point]	1.1
Perceptual-Motor	Click on "SURG General PreOp AZ" section	B [Mouse]	0.1
System Response: Show all Orders in section			
Subgoal C: Determine Appropriate Orders for Patient			
Action: Search Order Set for Relevant Orders			
Cognitive Process	Description	Operation	*Time (Sec)*
Working Memory	Decide what order appropriate to activate for patient	M [Locate]	1.2
Visual Search Working Memory	Locate the orders to activate	M [Locate]	1.2
Subgoal D: Activate Appropriate Orders			
Action: Select Orders to Activate			
Cognitive Process	Description	Operation	Time (Sec)
Visual Search Working Memory	Locate the orders order section to activate	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to order section to activate	P [Point]	1.1
Perceptual-Motor	Click on order section to activate	B [Mouse]	0.1
Visual Search Working Memory	Locate the “Activate” button	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to “Activate” button	P [Point]	1.1
Perceptual-Motor	Click on “Activate” button	B [Mouse]	0.1

7.5 Discussion

The presented analyses used the navigational complexity framework to analyze, document, and propose changes to EHR-mediated workflows post-conversion, as reflected in measures of interactive behavior. This work contrasted EHR-mediated workflows and evaluated how interface designs, including the distribution of functional elements, can affect navigational complexity and task efficiency. POM processes across two charting systems, pre-and post-implementation, from Mayo Clinic hospitals were compared by applying the navigational complexity framework. Differences were observed in the modes of interaction mediated by differences in interface designs.

By applying the navigational complexity framework, I can better understand how different EHR interfaces differentially mediate task performance and document changes after system implementation. This also allows for a deeper understanding of task complexities at a more granular level from a user perspective and expert analysis perspective. The application of the framework, using user-based and expert-based methods, versus a single method can validate and anticipate findings during a system implementation by identifying issues and design and determining if these design issues carry to the new system. The framework establishes a comparison tool that aims to align the user perspective with a usability expert feedback. This alignment is not possible while utilizing a single method in either only user-based or expert-based methods.

Differences in navigation and interface designs contribute to poor task efficiency. Providers often perceive EHRs as challenging to use. Usability analysts have further cited issues with difficult-to-read interfaces, confusing displays, and iconography lacking consistency and intuitive meaning (5). These usability issues often lead to an increased cognitive load. These challenges may surface when transitioning from one system or interface to another, causing disruptions to workflow and efficiency (62). We can better understand how different EHR interfaces differentially mediate task performance and document changes after system implementation by applying the navigational complexity framework. This also allows for a deeper understanding of task complexities at a more granular level.

7.6 Conclusion

The use of a navigational complexity framework helped identify interface design differences and how they can contribute to cognitive load and documentation burden. Expert-based and user-based analyses were applied to the analysis of a task before and after EHR conversion to understand better usability barriers at a more granular level and their effect on task performance and efficiency. The analyses completed in this chapter identified interface design elements that differentially mediate task performance. By establishing system comparison tools to identify potential usability barriers in a system, issues were identified to enhance the user experience, leading to a higher quality of care in workflow while informing optimization efforts.

8 CONCLUDING REMARKS

8.1 Introduction

The dissertation presented here utilized the first aim to present and explore the application of an innovative methodological framework to explore differences in task-specific EHR interfaces and the issues in usability they present. In aim one, the navigational complexity framework is presented to assess issues in navigation and EHR system use through a collection of expert-based and user-based methods to characterize and evaluate clinicians' EHR-mediated work and propose tractable improvements. In aims two and three, a two-phase validation of the framework is demonstrated. Phase one validation applied the framework to two routine EHR-mediated workflow tasks: medication reconciliation and medication administration record. This allowed for confirmation of the combination of methods. Phase two validation applies the framework pre- and post-implementation of an EHR, focusing on a routine EHR-mediated workflow task: patient order management. This second application phase of the framework validates that the framework can be applied across multiple systems, sites, settings, and tasks and that the execution of the framework is streamlined.

The structured evaluations presented in the navigational complexity framework provide more meaningful insights into user struggles and interface flaws that traditional interface and workflow analyses cannot. Complexities and variations in interaction cannot be fully captured with any one single method. The primary contribution of this dissertation is a robust framework to elucidate navigational complexity in EHR interfaces, a problem that was previously recognized as important but lacking in conceptual and methodological clarity. The framework not only acts as a tool for proposing improvements to interface design but acts as a generalizable guide that can be applied to any system, site, or setting.

8.2 Contributions of the Methodological Framework

The navigational complexity framework contributes a theoretically grounded, structured, methodological approach for elucidating navigational complexity. This allows for a broader understanding of issues users face with navigating and interacting with an interface at the moment-by-moment experience. The combination of quantitative and qualitative data offers a method of precision and higher reproducibility. This precision was facilitated by the Morae™ video recordings of users, allowing for manual coding of interactions for analysis. A review of these recordings provided an in-depth analysis of individual interactive behaviors and microstrategies for navigating EHR interfaces. The clickstream analysis presented in the framework, coupled with the modified walkthrough, enables segmentation of the sequential task process and user experience at the micro-analytic level needed to surface challenges that users encounter and characterize them in a meaningful way.

The navigational complexity framework has the intention of functioning with a reduced set of methods (e.g., emphasizing expert-review methods) being used as a practical tool to evaluate EHR task interfaces and to fashion human-centered design solutions within a specific interface. The framework is applied to the PreOp nurse patient check-in process specifically in this work. However, the framework can be applied to any workflow or specific process identified by the organization leveraging the workflow. Validation of the workflow was completed with PreOp data due to the quality of data collected and the volume. Workflow is embedded in a more complicated overall clinical process, which has boundaries that stretch beyond task performance. Because of the complexity of overall clinical workflow, the framework was validated using the isolated PreOp nursing workflow. However, it is applicable to any clinical workflow or task of focus.

Analysis revolved around expert-based and user-based methods to characterize differences in interactive behavior measures and their impact on performance. This combination of methods explains how the interface forms constrain EHR-mediated workflow and how that is manifested in interactive behavioral measures. The combination of methods was applied to one of the greatest strengths of the work, the multiple data streams that are generated and organized for analysis. These data streams provide a thorough understanding of the complexities involved with task completion.

8.3 A Cognitive Engineering Approach

While there are a number of categorization and methodological frameworks that leverage methods, the theoretical background that integrates cognitive engineering into these frameworks is missing. The CE approach can guide evaluations of user performance and match the design of a tool or system with the user based on their needs while maximizing performance.

An advantage of cognitive engineering is its dual focus on elucidating the range of system complexities that can potentially impact cognitive performance using expert methods and the user strategies that enable practitioners to cope with these demands (4,7,93). The methods uncover different kinds of problems and, when used in context, provide a richer multidimensional portrait of health information systems and user experiences. In recent times, innovative approaches have combined and extended these methods in novel ways to provide a more penetrating analysis of the user experience in healthcare contexts. In a related study, we examined the ways in which practitioner strategies compensate for the litany of EHR-mediated workflow problems, including navigational complexity as it manifests itself across tasks (45,72).

The CE theories that influence the framework and associated methods presented in the navigational complexity framework is a novel approach to integrating quantitative and qualitative analysis through user-based and expert-based approaches. This allows for a more in-depth quantification of EHR interactions and justifies variation between users, systems, and settings. These detailed insights can be used for interface improvement to maximize user satisfaction and minimize burnout.

8.4 Framework Limitations

There are several potential limitations. The study employed a small sample size, and many factors impact workflow. However, the fusion of both expert review methods and user analysis allows greater confidence in the validity of these findings. Also, the study focused on navigating specific pathways to complete a task. It is a relatively finite problem space in that task completion is sequential (i.e., one goal or subgoal at a time), and there are only a small number of ways in which the task can be executed. In addition, a microanalytic approach enables us to cross-reference subgoals derived from the walkthrough with clickstream data for a single clinician to identify task segments that are problematic. We can further characterize the problems in terms of interface elements employing a representational analysis and yield meaningful data with few participants. Recently, we have coupled this approach with process mining to explore large log file data sets, which enable us to characterize thousands of events, albeit at a coarser level of granularity (73)

The use of the KLM method has limitations in relation to its precision (94). It was designed to model an expert path or workflow process. However, it is based on a small number of presuppositions for quantifying time to complete a task. It is unclear whether the specific tasks selected are the most important ones in the overall use of the EHR. It does not include the impact of expertise or experience, which can significantly impact performance. As such, it is a very useful but not a sufficiently precise measure.

Another limitation is that the constructs of working memory and visual search were analyzed qualitatively in this paper. There is no concrete way to yet apply a true qualitative value to visual search and working memory, while perceptual-motor behavior is represented through mouse clicks and screen changes. These constructs can be quantified more precisely gauged by using eye-tracking methods (46,95).

Additionally, the approaches described in this work are rather labor-intensive, time-consuming, costly, and necessitates substantial expertise to execute. It is also difficult to secure privileges to video record clinicians in live clinical settings. The framework describes an underlying theory, a set of measures, and ways to conceptualize problems or features that result in complexity that extends beyond the specific measures used in this paper. Although there is value in the integrity of a more comprehensive granular approach, it is possible to employ this framework without engaging the full complement of data collection and methods of analysis.

8.5 Conclusions and Future Work

Navigational complexity has an undeniable impact on the burden experienced by clinicians when using an EHR. In this paper, we introduce a new methodological framework to model the navigation of EHR-mediated workflow. Different interfaces differentially mediate task performances, as reflected in interactive behavior. The analysis surfaced design tradeoffs. A future goal is to identify the suitable task-specific configuration of the EHR component parts (e.g., tables, widgets, search fields, dialogue boxes, etc.) that facilitate efficient performance and diminishes cognitive load. We anticipate designing and testing prototype or mockup interfaces that embody changes to an original design with the intent of reducing measurable navigational complexity.

The navigational complexity framework can be modified to match the specific circumstance by utilizing a reduced set of methods (e.g., emphasizing expert-review methods) being used as a practical tool to evaluate EHR task interfaces and to fashion human-centered design solutions. The framework can lead to evidenced-based small tractable changes that improve efficiency, streamline EHR-mediated workflow, and greatly enhance the user experience.

Future work could involve more precise quantitative modeling and the use of simulation methods to test different potential navigational trajectories. The micro-analytic approach necessitates scrutiny of a small number of subjects along with extending this framework to other clinical tasks, such as patient order management. The navigational complexity framework is not exclusive to the PreOp setting, and is generalizable to any EHR-mediated workflow in clinical practice. The set of methods proposed can function as a practical tool to evaluate EHR task interfaces and to fashion human-centered design solutions across any system, clinical site, or geographical setting. As long as an EHR is involved in the workflow, the navigational complexity framework can be used to identify and propose system improvements. All that is needed is a clinician of focus and the EHR the clinician interacts with.

The EHR-mediated workflow in clinical continues to become more complex, integrating different systems, artifacts, and patient complexity. The development of complexity in health IT also continues to present formidable challenges for users and developers. However, the growing body of work in the study of cognition and clinical workflow has the potential to yield insights and contribute instrumentally to the solution space for optimal design. A deeper understanding of EHR-mediated workflow and user needs can bring the work closer to achieving a holistic approach to IT design.

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APPENDIX A

PDF IMAGES OF THE ORIGINAL JBI PUBLICATION

1.0 Abstract

Clinician task performance is significantly impacted by the navigational efficiency of the system interface. Here we propose and evaluate a navigational complexity framework useful for examining differences in electronic health record (EHR) interface systems and their impact on task performance. The methodological approach includes 1) expert-based methods—specifically, representational analysis (focused on interface elements), keystroke level modeling (KLM), and cognitive walkthrough; and 2) quantitative analysis of interactive behaviors based on video-captured observations. Medication administration record (MAR) tasks completed by nurses during preoperative (PreOp) patient assessment were studied across three Mayo Clinic regional campuses and three different EHR systems. By analyzing the steps executed within the interfaces involved to complete the MAR tasks, we characterized complexities in EHR navigation. These complexities were reflected in time spent on task, click counts, and screen transitions, and were found to potentially influence nurses' performance. Two of the EHR systems, employing a single screen format, required less time to complete (mean 101.5, range 106-97 seconds), respectively, compared to one system employing multiple screens (176 seconds, 73% increase). These complexities surfaced through trade-offs in cognitive processes that could potentially influence nurses' performance. Factors such as perceptual-motor activity, visual search, and memory load impacted navigational complexity. An implication of this work is that small tractable changes in interface design can substantially improve EHR navigation, overall usability, and workflow.

2.0 Background and Significance

Healthcare institutions have invested tremendous time, money, and effort into implementing or converting to, new electronic health records (EHRs), with the expectation that EHRs will enhance productivity (1). However, clinicians are often dissatisfied with EHRs that do not support their cognitive workflow and information needs (2,3). EHR interface designs are frequently inefficient and unintuitive creating difficult user experiences (4–7). Problematic EHR navigation, for example, switching between interfaces, can carry cognitive consequences (8), such as the "keyhole effect", a well-documented problem in human-computer interaction (HCI) research (9). The keyhole effect can occur in EHRs when an abundance of patient information is made available through the narrow lens afforded by an EHR display. This is analogous to peeking through a keyhole in a door to see what is in a room. This problem can create a significant EHR usability bottleneck (10). In this paper, we investigate how interface design impacts navigational complexity with a focus on observations of the medication administration record (MAR) task in pre-operative (PreOp) assessment on different EHR systems.

Our work draws on cognitive engineering (CE), an interdisciplinary framework for the development of principles, methods, and tools used to assess and guide the design of systems to support human performance. CE highlights the discrepancy between the user's goals and the physical controls embodied in a system (11–13). Interactive behavior can be analyzed as a combination of elementary cognitive, perceptual, and motor behavior (14). Certain task-system combinations may be more memory-intensive or require more in the way of perceptual and motor behavior (12). Also, the users of any information system divide their cognitive resources between navigating through the system interface and performing the specific tasks at hand (e.g., documenting a patient's vital signs) (15). CE methods can provide a more direct link between the results of cognitive analyses and elements of a new system or interface redesign (13). It can be used to create heuristics or guideposts that streamline the EHR navigational experience.

Following Roman et al., we define EHR-based navigation as "desktop-based interaction with user interface presentation and controls that allow users to locate and access needed information" (8). Navigation characterizes the route taken to complete a task, including the action steps (e.g., mouse clicks) and the traversal through space (e.g., moving a mouse across a display or negotiating successive screens). Roman et al. distinguish between-page navigation (action to move to a new page in an EHR) from within-page navigation (actions to move within a given page) (8).

To add a degree of theoretical precision to Roman et al.'s definition, we construe navigation as guided by *function* (such as medication administration documentation), constrained by *form* (i.e., the display configuration) and manifested in terms of *flow* (the sequence of activities related to task completion). The form or configuration of specific interface elements such as screen layout, dialogue boxes, and pulldown menus can contribute to varying levels of optimality or complexity in system interaction. There is considerable variation in form across EHRs for the same task, such as medication reconciliation (2,8). Optimizing the form in which information is displayed, accessed, and edited is predicated on identifying and understanding the flow of specific tasks. For a given task, navigational complexity can be operationalized and measured in terms of the flow or level of interactivity (e.g., number of mouse clicks). Flow can be idealized as a seamless task performance without disruption or repetition that maximizes the allocation of cognitive resources to the task at hand. The study of navigational complexity bridges the divide between static usability evaluation (e.g., as reflected in usability inspection or lab-based usability testing studies) and workflow. The term *complexity* has a wide range of meanings as used in informatics and more broadly in scientific research (11). In this context, navigational complexity is a narrowly construed measurable construct that reflects the degree of difficulty in executing the steps in an EHR task. Although we construe complexity as a property of a given system in the context of performing a specific task, there is no absolute measure or statistic to quantify it. We employ a comparative approach to the study of EHR use as a starting point for characterizing relative navigational complexity.

Increases in navigational complexity will necessitate that more resources be devoted to interacting with the system and less to thoughtful task completion. By scrutinizing seemingly small interface design differences through a micro-analytic approach, we can better identify and quantify variation in processes and examine their impact on task completion. The micro-analytic approach involves a more granular level of analysis of both the user and the system behavior. It can characterize interactions (e.g., mouse clicks) with the system at a moment-to-moment level with a high level of detail (16). It enables us to model task behavior with a higher level of precision with relatively few subjects.

The study reported in this paper builds on our prior work in the study of navigational complexity. Duncan and colleagues studied vital signs documentation and medication reconciliation tasks in the EHR, characterizing how different charting interfaces mediate task performances across clinical sites (4,17). The study documented how the configuration of interface elements created unnecessary navigational complexities when interacting with the system. The research was conducted as part of The Registry of Operations and Tasks (ROOT) Project, which characterized EHR-mediated workflows throughout the Mayo Clinic organization, focusing on EHR use in surgical and emergency department settings (18,19).

In this paper, we introduce a novel navigational complexity framework that leverages both expert review and user testing methods to explore differences in task-specific EHR interfaces. This project characterizes and quantifies how these differences impact interactive behavior. We build on a recent paper by Calvitti et al., which employed methods for capturing, analyzing, and visualizing EHR use and clinical workflow of physicians during outpatient encounters (17). The framework also draws on the TURF (task, user, representation, and function) EHR usability framework, which describes, explains, and predicts usability differences drawing on objective, quantifiable measures (16).

3.0 Methods

3.1 Study Settings and Participants

This study was conducted in the PreOp setting at three Mayo Clinic regional campuses: Mayo Clinic Hospital, Phoenix, Arizona (AZ); Mayo Clinic Hospital, Jacksonville, Florida (FL); and Mayo Clinic Health System-Eau Claire Hospital, Eau Claire, Wisconsin (WI). Participants included 11 PreOp nurses across all sites and a total of 15 distinct patient cases. We observed nurses working on one or two individual cases.

3.2 Institutional Review Board

The study and its proposed procedures for the protection of human subjects were submitted to the Mayo Clinic Institutional Review Board (IRB). Since the project was designed primarily for quality improvement and system redesign purposes, it was deemed exempt. The Arizona State University IRB also reviewed the study protocol and concurred with the Mayo Clinic IRB assessment.

3.3 Systems Used

In the Arizona campus, the primary tool used for charting was Cerner SurgiNet. All patient information was accessed and updated through this application, along with patient tracking. In

Florida, the main tool used for charting was Cerner SurgiNet with the additional use of Cerner PowerChart for completing the MAR task. In the Wisconsin campus, the primary tool used for charting was Surgical Information Systems (SIS).

3.4 Data Collection

We observed surgical staff performing their everyday work *in-situ*, on a variety of patients in a PreOp setting between 2016 and 2017. We employed Morae™ 3.3 for video recording. This video analytic software was used to capture workflow. The data was collected over a period of two weeks at each site. The software records the clinician-user's on-screen actions, providing a set of analytics (e.g., mouse clicks, web-page changes, etc.), and audio and video recording of the clinicians' hands (e.g., use of paper documents, checklists) via a webcam. An observer with a hand-held camera was also present during the data collection to record points of interest during observations. A total of 14 hours of video recordings were captured across 11 different nurses over 10 days at the three different clinical sites, which are presented in this work. When possible, nurses voiced their thoughts as they performed the task (think-aloud protocol).

3.5 Data Analysis

As illustrated in Figure 1, the methodological approach includes expert-based methods, comprising (1) representational analysis (RA) (focus on interface elements), (2) keystroke-level modeling (KLM), and (3) cognitive walkthrough. User-based methods consist of (4) quantitative behavior measures based on observation and (5) visualization of distinct user clickstream data to observe variation across users completing tasks. The segmentation and coding of EHR tasks (not represented in Figure 1) is an essential first step for both expert-based and user-based methods. The RA, KLM, and cognitive walkthrough are combined to identify optimal execution times and associated cognitive processes. The last phase involves integrating expert and user-based methods to determine how specific interfaces constrain interactive behavior.

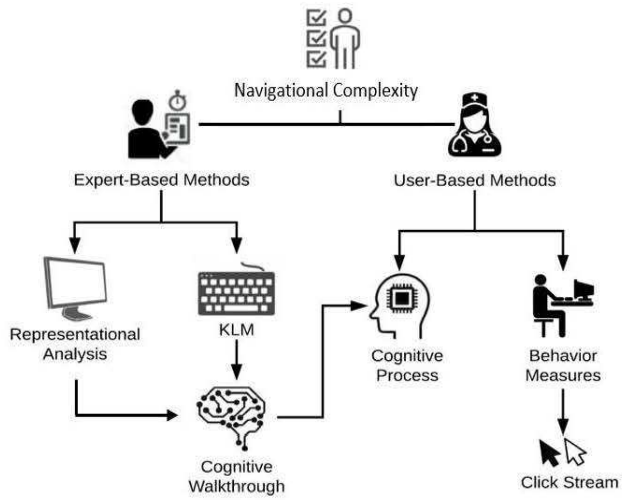

Figure 1: Methods were separated into two categories, expert-based methods and user-based methods used for analysis

3.5.1 Segmentation of Clinical Tasks

To develop a task list, we (1) reviewed recorded screenshots and videos, (2) examined frequency distribution/sequential break down of EHR activities, (3) reviewed policies applicable to Surgical Services on the Mayo Clinic Intranet, and (4) compared the videos from the different sites. Of the tasks segmented, this paper focuses on MAR, a prominent task from the PreOp nursing assessment. The MAR is a report that serves as a record of all medications or drugs administered to patients throughout their care (20,21). Videos were reviewed for integrity and to identify segments of time where no EHR activity was observed then segmented into individual tasks. Once segmented, the MAR task was reviewed, and expert-based analytic methods and user analysis were performed.

3.5.2 Expert-Based Methods

Three interrelated analytic methods were used to model the process of completing a task while assessing task performance overall. RA describes and evaluates the appropriateness of the representations for a given task and a given type of user (22). RA shares a common purpose with the method employed in the TURF (16). However, the TURF granularly analyzes information display's dimensions based on a taxonomy. The focus of RA in our work was on the form of a section of a display (e.g., a panel), how it might impact cognition and its connection to the stream of the workflow. The analyses were performed by the first author (BD) with the assistance of the senior author (DK).

The KLM analytic method evaluates the set of operations and the time required to complete a given task. In the KLM model, there are six operators: key button press and release (K), mouse pointing (P), moving hands to the home position on the keyboard or to the mouse (H), button press (B), mentally preparing to perform an action (M), and typing a string of characters (T(n), n*K seconds) (23). Each action has estimated execution: K is 0.20 seconds, P is 1.10 seconds, H is 0.40 seconds, B is 0.10 seconds, M is 1.20 seconds, and T(n) is 0.20 * n seconds. Thus, the KLM model for a specific task can be constructed by identifying each operation needed to complete the task and summing together the execution time for each operation. The KLM, therefore, represents the time taken to complete a task if it were done with no errors or interruptions. The constructed KLM can then be compared with observed user data. Although KLM was designed to model errorless task execution of routine tasks, it is a reliable indicator of effort in various studies across a wide range of platforms (23,24). We have found it to approximate users' performance across time measures well (2).

The cognitive walkthrough is a commonly used method for analyzing interface complexity and usability (25,26). It involves characterizing a sequence of actions and goals for completing a task. For this study, the method allowed for evaluation of how well the system supports the user to complete the task and for the identification of the complexities faced by the user. The KLM and cognitive walkthrough analytic methods were combined to examine how specific goals and subgoals are enabled when working through the steps of a task. The combination of these methods into a modified walkthrough provided insight into the specific actions involved with goals and subgoals. Nested within each of the subgoals were specific actions to complete the subgoals. This combination of methods provided an estimation of the time to task completion, given a relatively optimal set of steps in an ideal setting. We also characterize the cognitive processes associated with steps in task performance. Perceptual-motor processes were associated with mouse clicks, scrolling, and keyboard activities. Search was reflected in locating information across screens, menus, and dialog boxes where a user must select from a variably lengthy list of choices. *Memory load* was a function of the need to maintain information gleaned from one screen to perform actions on the next screen. Subgoals are a primary focus of analysis and form the basis for tractable changes to interface elements which can lead to measurable differences in performance.

We used RA in conjunction with the cognitive walkthrough to identify the functions associated with specific display elements. Each function was considered to be a subgoal of the overall task. Specifically, the analyses examined how different interface presentations (i.e., form) support navigation to evaluate the appropriateness of representations for the given user performing a selected task or function. This approach enables us to isolate specific aspects that contribute to task inefficiencies or cognitive load and possibly target them for future redesign efforts.

3.5.3 User-Based Methods

Expert and user-based methods can be used independently as they have in many studies, but employing them in concert provides a more comprehensive picture of navigational complexity. The expert-based methods provide guidance to the source of navigational complexity at a granular level and enhance the explanatory power of empirical results of user studies. They can also be used to predict differences in system comparison. The user-based methods provide a real-world acid test for the expert analyses and provide additional insights into navigational complexity. Expert-based methods are ideal for modeling relative fixed navigational pathways, for example, where the interface determines the action sequence. User-based methods are particularly important for surfacing problems where the interface design affords more degrees of freedom and where we are likely to observe greater variation in interaction.

We gathered interactive behavior measures (mouse clicks, screen changes) and clickstream data for each user which formed our user-based data. With this data, we compared interactive behaviors across users, systems, and clinical sites. Interactive behavior measures were automatically generated in Morae based on the segmentation of tasks. These interactive behavior measures were then inserted into a clickstream graph showing each an event of a mouse click for a selected task across the whole workflow.

3.5.4 Partitioning Data Activity Streams

The data streams used in the analyses are presented in Figure 2. The figure illustrates how we aggregated the temporally-based user data and combined it to understand task complexities at a more granular level in novel ways. Initially, tasks were segmented, and analytics were generated for each task (Figure 2, section A). Once the tasks were identified, the individual clickstream data for each occurrence of the task were modeled (Figure 2, section B). Following clickstream, actions associated with the selected tasks, such as keystrokes for each task, were generated (Figure 2, section C). Timebelt visualizations were created to show the ordered sequence of tasks for a given patient case (Figure 2, section D) (27,28). A description of each data stream is provided below.

Figure 2A represents manual task coding of screen captures of EHR activity during the nursing PreOp assessment. The audio stream indicates vocalizations as reflected in the think-aloud protocol and conversations with other individuals (e.g., other clinicians and patients) captured via the webcam to understand the overall workflow. Tasks are coded sequentially, and analytics regarding each task was generated (mouse clicks, screen changes, time on task) automatically by Morae. These interactive behavior measures were then converted into clickstream data for each user.

A timeline representation showing when various clicks occurring for the MAR task is presented in Figure 2B. In this figure, the three lines represent three discontinuous instances of MAR occurring throughout the assessment. There were bursts of clicking activity, which reflects perceptual-motor processes. There were also extended intervals between mouse-clicks, which tend to coincide with visual search processes. We also used the clickstream data to mark the beginning and completion of specific subgoals (e.g., save medication details) related to task execution. This connects the clickstream to both the representational analysis (spatially) and the walkthrough (temporally).

Additional analytics were generated to provide a further understanding of interactive complexities involved in task performance, such as keystrokes (Figure 2C). The keystrokes for the MAR task were relatively sparse as most data entries involved menu selection and were not included in further analysis. Other tasks involve more written documentation, and the keystroke stream takes on greater importance in characterizing navigational complexity.

Once the order of tasks was generated from analyzing recordings, a visualization to show the frequency of task switching within EHR-mediated workflow was generated (Figure 2D). The visualization of these various data streams was intended to show how each point of analysis builds on the previous to provide additional insight and context into EHR-mediated workflow. We employed the visualization to mark the beginning and end of a task and note when a task has multiple instances for a PreOp patient case. In a separate paper, we examined the continuities and discontinuities of task performance across the entire patient case to model the task fragmentation in the clinical workflow (27). Figures 2C and 2D are used to illustrate the process of analyzing data streams and are part of the overall navigational complexity framework, but no further analysis of these specific streams are presented in this paper.

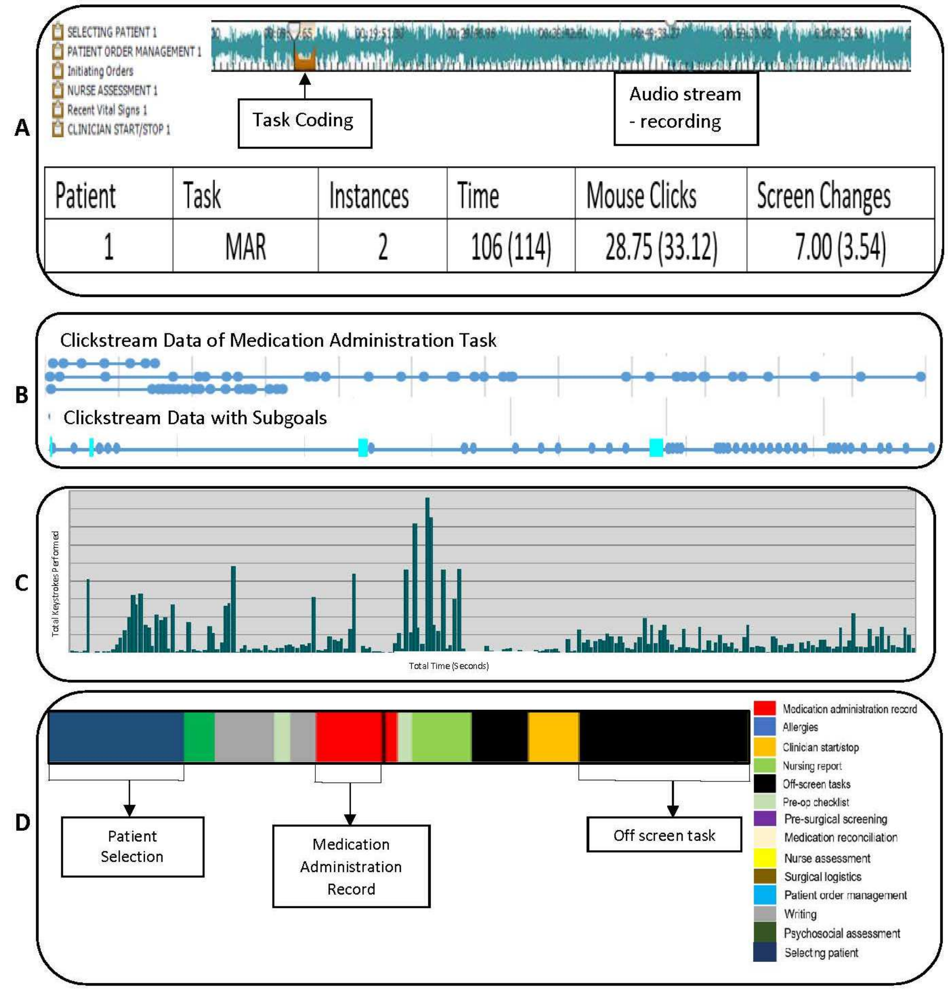

Figure 2: Data streams for a single nurse and one patient. A Morae video timeline with individual task coding and interactive behavior measure for the selected task. B Clickstream data for a single instance of the task. Each line represents a new instance or a restart of the task. In the top half of figure B, there are three instances of the MAR task for a single patient. This indicates that the task was started and stopped on multiple occasions during the PreOp assessment. In the second half of the figure, we use markers to denote task subgoal beginnings and completions. This enables to coordinate user actions with specific steps of the cognitive walkthrough and sections of the display. C Keystroke data generated from Morae analytics detailing keystrokes and frequency of occurrence. D Entire PreOp assessment segmented by tasks. The time belt visualization shows selected tasks for a single patient visit. The visualization highlights ordered sequence of tasks and discontinuities in task completion.

4.0 Results

4.1 Expert-Based Results

The following presents the results of the expert-based methods – RA, KLM, and CW – which have been combined to show both the form and function of the MAR task, as well as the flow of the task. Table 1 shows the functions of the task, represented as goals, and subgoals for each EHR, and the associated function. The results in this table are distilled from the individual walkthroughs and representational analyses which are described in subsequent sections.

Table 1: Analysis of the function and form for MAR task for three EHR Systems based on CW and RA methods. The grey boxes indicate that the form does not exist in the specified system

Goals and Subgoals	Form		
	SurgiNet	PowerChart	SIS
Goal 1: Transition to MAR Screen			
Subgoal A: Locate "MAR" Menu Choice	Select menu column	Tab at top of the page	Locate choice using dropdown menu under wizard sets
Subgoal B: Select "MAR" menu choice Selection	Select from medication list, generated by screen	Select from pop-up window, which displays all medications	Select from dropdown menu leading to pop-up window
Goal 2: Document Medications			
Subgoal A: Select the desired medication	Select from medications displayed in columnar format	Select medication from in pop-up, no additional action required	
Subgoal A*: Document medication start time			Select medications available with dropdown menu
Subgoal B: Enter details of the medication	Enter medication details on previously generated pop-up window. Enter via static buttons and dropdown choices	Automatically upload via barcode scanner	
Subgoal B*: Modify personnel details			Select staff member name entering medication into MAR
Subgoal C: Save modified medication details	Select checkmark symbol	Click "Sign" button on the bottom of the generated pop-up screen	Click on next button
*Denotes alternative subgoals unique to a particular EHR system			

Table 2 for SurgiNet (Arizona) represents the flow of task completion. Complete walkthroughs for Arizona and Wisconsin sites are included in Appendices A and B. The table is organized to present goals and subgoals involved with task completion. Each of these goals and subgoals includes a description of the sequential process or flow, actions involved, time to complete this part of the task and characterization of demands on cognitive processes. These are coordinated with the results of the RA with interface representations that highlight specific design elements and representations of information shown in Figures 3, 4, and 5. These results indicate that the tasks are realized in different ways across the systems, which is elaborated in sections 4.1 and 4.2. Sections 4.3 and 4.4 present observational or user-centered data, explaining how the interface forms constrain EHR-mediated workflow and how that is manifested in interactive behavioral measures. The table also illustrates an integrative methodological approach.

Table 2: Combination of cognitive walkthrough and KLM for SurgiNet representing flow of activity

Cognitive Process	Description	Operation	Time (sec)
Goal 1: Transition to MAR Screen			
Subgoal A: Locate "MAR" Menu Choice			
Action: Search Menu for the "Orders-Charges" Selection			
Visual Search Working Memory	Locate "MAR" button	M [Locate]	1.2
Subgoal B: Select "MAR" menu choice Selection			
Action: Click on "Orders-Charges" Choice under Menu Options			
Perceptual-Motor Visual Search	Point to " MAR " button	P [Point]	1.1
Perceptual-Motor	Click on " MAR " button	B [Mouse]	0.1
System Response: Generates MAR			
Goal 2: Document appropriate medications			
Subgoal A: Select the desired medication			
Action: Select medication			
Working Memory	Determine what medications are appropriate to document	M [Locate]	1.2
Visual Search Working Memory	Locate the appropriate medication	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to the appropriate medication	P [Point]	1.1
Perceptual-Motor	Click on the appropriate medication	B [Mouse]	0.1
System Response: Medication detail pop-up screen generated			
Subgoal B: Enter details of the medication			
Action: Enter medication information			
Visual Search Working Memory	Locate "Not given" checkbox	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to "Not given" checkbox	P [Point]	1.1
Perceptual-Motor	Click on the "Not given" checkbox	B [Mouse]	0.1
Visual Search Working Memory	Locate appropriate "Reason" dropdown menu	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to appropriate "Reason" dropdown menu	P [Point]	1.1
Perceptual-Motor	Click on the "Reason" dropdown menu	B [Mouse]	0.1
Visual Search Working Memory	Locate appropriate reason for "not given"	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to appropriate reason for "not given"	P [Point]	1.1

Cognitive Process	Description	Operation	Time (sec)
Perceptual-Motor	Click on appropriate reason for "not given"	B [Mouse]	0.1
Subgoal C: Save modified medication details			
Action: Select Save selection			
Visual Search Working Memory	Locate save checkmark	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to save checkmark	P [Point]	1.1
Perceptual-Motor	Click on save checkmark	B [Mouse]	0.1
System Response: Saves medication details			

4.1.1 Goal 1: Transition to Medication Administration Screen

This section provides detailed descriptive results of the RA, KLM, and Cognitive Walkthrough methods which will provide a detailed look at the form, function, and flow of the MAR task and how it differs across the three EHRs. The same applies to Goal 2 (4.1.2).

4.1.1.1 Subgoal A: Locate "MAR" Menu Choice

The first subgoal involved in the completion of the MAR task is locating the MAR menu choice for SurgiNet and PowerChart. However, in SIS, the first subgoal varies due to different interface layouts. The subgoal for SIS is "Locate PreOp Medications Selection". Each system had different representations and interface designs for screen layouts. In SurgiNet, the option for navigating to the MAR screen is located in a menu column for quick transitions between various sections of the EHR. This selection is labeled as "MAR" (Figure 3A). In PowerChart, the process varies slightly. The "Medication Administration" tab is shown at the top of the page with a series of other shortcut tabs (Figure 4A). In SIS, a dropdown menu is utilized, titled "Wizard Sets", that allows for navigation through interface sections (Figure 5B). In all three systems, the only step involved with this subgoal is to locate the system-specific option within the interface. The KLM estimated time is 1.2 seconds to perform this action and subgoal. This makes demands on visual search cognitive processes as the clinician must search through a dense interface for the desired menu option.

4.1.1.2 Subgoal B: Select MAR Selection

Once the menu option is located, the second subgoal is to select the option to generate the MAR interface. Although there are different representations of information, the modes of interaction are primarily the same between the systems. In SurgiNet, the menu item of "MAR" is selected, and the screen generates a medication list. Medications are sorted into three main categories, "Scheduled," "Unscheduled," and "PRN" (Figure 3B). In PowerChart, the "Medication Administration" tab is selected, and a newly generated pop-up window displays all medications for the selected patient (Figure 4C). In SIS, the mode of interaction varies, where a selection from a dropdown menu is made rather than a menu choice, generating a new pop-up window where medication details are entered (Figure 5C). In both SurgiNet and PowerChart, the KLM resulted in single actions and similar total times, with two steps required in the action. The system requires users to point to the desired menu choice and click on it, requiring an estimated 1.2 seconds to complete both actions. This facilitates both the perceptual-motor and visual search cognitive process, with perceptual-motor actions being prominent, requiring users to move the mouse and click the selection. In SIS, the mode of interaction within the interface differs widely, requiring two separate actions with a total of 8 steps. Users select the appropriate option from the dropdown menu and then make a second selection to navigate to the MAR section on the generated pop-up screen. This requires about 6.0 seconds to complete all actions for the interface mentioned above. In SIS, there are roughly equal amounts of the perceptual-motor actions and visual search cognitive processes. This is primarily due to the number of actions necessary, requiring users to perform more physical actions and requiring users to locate several menu options within the interface.

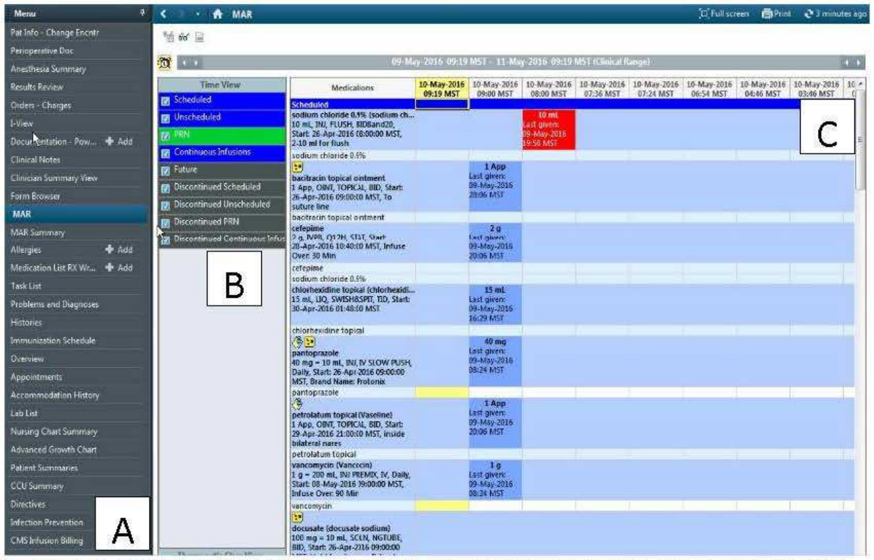

*Figure 3: Medication Administration interface used in SurgiNet. **Section A** represents the menu choices to navigate to MAR, **Section B** is the "Time View" section for time categories of medications, **Section C** is where medication details are displayed and charted*

4.1.2 Goal 2: Document Appropriate Medications

For Goal 1, users navigate to the correct interface to complete the MAR task. Goal 2 addresses the documentation of current medications for a patient. The main difference in this goal across the different interfaces is the mode in which medication details are entered. In SurgiNet, medications are categorized by the times at which medications are scheduled for administration (i.e., scheduled, unscheduled, PRN medications) with details displayed in a columnar layout (Figure 4B). Once a category is selected, the appropriate medications are shown and organized based on the date and time. This is where individual medication details (i.e., date received, time is given, and dosage) are entered and stored (Figure 3C). When the desired medication is selected, a pop-up window is generated, and medication details are manually entered.

4.1.2.1 Subgoal A: Select the desired medication

In SIS, the subgoal is *Subgoal A: Document medication "Start Time"* which is different from the other systems. In the previously generated pop-up screen in SIS, the desired medication is searched and a current list is not shown (Figure 4C). The KLM resulted in a single action containing five individual steps to complete. The estimated action completion time is 4.8 seconds while requiring considerable working memory to remember the medication administration time and perceptual-motor actions to log this information. In SurgiNet, the KLM resulted in a single action and four distinct steps with an estimated total time of 3.6 seconds to execute. These steps facilitated significant perceptual-motor activity and visual search through the need to find the appropriate medication from a list and physically selecting the medication. The KLM resulted in a total of 3 different actions with a total of 10 total steps. The total time to complete this subgoal was estimated to be 9.2 seconds.

4.1.2.2 Subgoal B: Enter medication details

After selecting the appropriate medication, the next step in the MAR task is to enter the specific medication details. In SurgiNet, all medication details are entered on the previously generated pop-up window with a series of static buttons and dropdown choices used for data entry (Figure 3C). In PowerChart, because medication details are automatically uploaded with minimal edits via a barcode scanner, the next subgoal is specific to PowerChart, *Subgoal B: Save modified medication details*. Once all appropriate medications are scanned, the "Sign" button on the bottom of the generated pop-up screen is selected, and medication details are saved within the MAR (Figure 4C). In SIS, all necessary medication details were previously entered, resulting in *Subgoal B: Modify personnel details*. Here, the clinician administering the medications is documented within the MAR (Figure 5C). In SurgiNet, this subgoal resulted in a single action with 9 total steps involved, generating a KLM estimate of 7.2 seconds to execute. This facilitated several perceptual-motor activities to navigate through the interface and visual search to locate the specific fields for data entry. In PowerChart, the subgoal required one action containing a total of 6 individual steps, generating KLM estimates of 4.8 seconds to execute these steps. Like SurgiNet, there was a significant dependency of perceptual-motor actions and visual search when navigating through the interface and locating the various fields for data entry. In SIS, the subgoal required two distinct actions with the first action containing 3 individual steps and the second action containing 4 individual steps, generating KLM estimates of 2.4 seconds and 3.6 seconds. SIS facilitated an equal portion of working memory, visual search and perceptual-motor action being that the subgoal required the user to remember they administered the medication (working memory), locate the various correct options and data fields (visual search) and navigate through the interface to enter the data (perceptual-motor).

4.1.2.3 Subgoal C: Save modified medication details

Once the medication details are entered, this information must be saved into the MAR. This task is only completed in SurgiNet and SIS and using different formats. In SurgiNet, the user selects a small checkmark symbol in order to save all entered medication details into the MAR. A saving function is also completed in SIS; however, the process differs considerably. In SIS, the user located the “Next” button, and by selecting this, saves all entered medication details into the MAR (Figure 4C). In SurgiNet, the subgoal requires one action that involves three individual steps resulting in a KLM estimate of 2.4 seconds. This process primarily facilitates visual search and perceptual-motor activity, requiring users to locate the correct menu option and move the mouse to select the correct option. In SIS, there is a single action that requires four individual steps resulting in a KLM estimate of 3.6 seconds. This difference is due to user’s deciding if all medications are recorded in SIS while SurgiNet uses individual pop-up screens for each medication. This process primarily facilitates visual search and perceptual-motor activity, requiring users to locate the correct menu option and move the mouse to select the correct option.

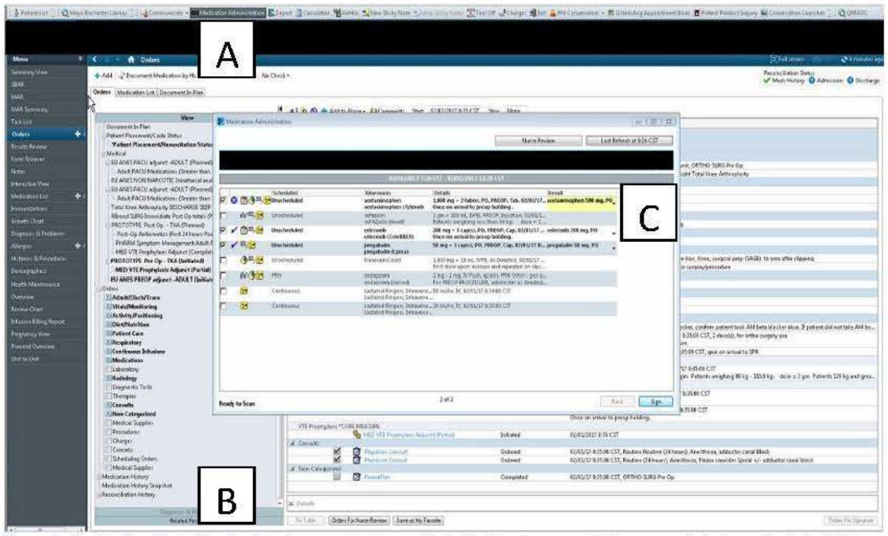

*Figure 4: Medication Administration interface used in PowerChart. **Section A** represents the menu choice to navigate to MAR, **Section B** is the medication categories, **Section C** is where medication details are displayed and charted.*

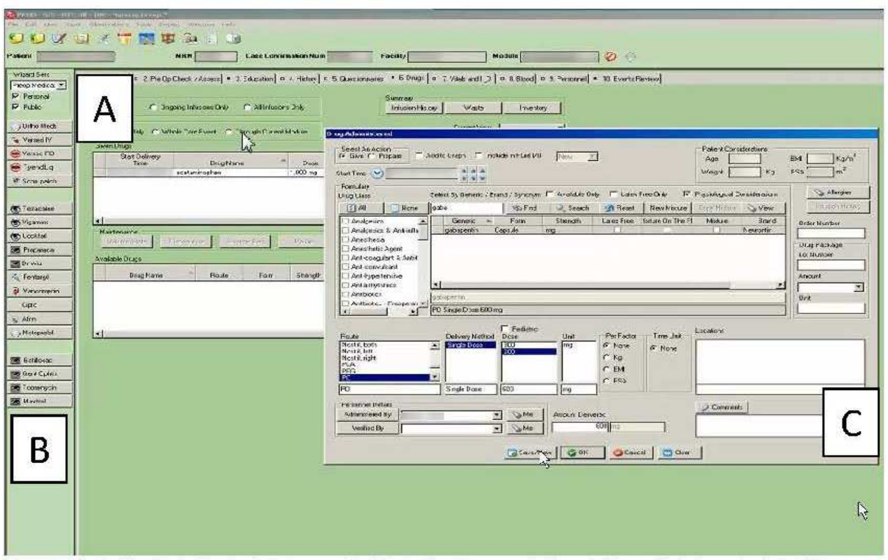

*Figure 5: Medication Administration interface used in SIS. **Section A** represents the selections of tabs to navigate to MAR, **Section B** is the medication sections, **Section C** is where medication details are displayed and charted.*

4.2 User-Centered Results

4.2.1 Interactive Behavior Measures

Table 3 represents the observed interactive behavior measures when completing the MAR task across all sites. These measures provide insight into task performance and aim to quantify the burden of documentation from navigational complexity placed on clinicians. In turn, these are used as comparisons to the measures derived from the expert-based methods to determine how the observed compares to the ideal. At the Arizona and Florida campuses, there was general consistency in the total time for task completion with 106 (SD: 114) and 97 (39) seconds. In contrast, Wisconsin required 176 (46) seconds to complete the entire MAR task. The Florida MAR process involves the scanning of medications rather than manual entry. This difference in procedure is seen in the mouse clicks, where Arizona and Wisconsin had higher counts at 28.7 (33.12) and 27 (0.82), while Florida required 12.7 (2.17) clicks.

Table 3: Interactive behavior measures for the MAR task across all sites

Task completed/ All cases)	Mean (SD) of Time (sec)	Mean (SD) of Mouse Clicks	Mean (SD) of Screen Changes	Actual Time (sec)	KLM (sec)
Arizona (6/8)	106 (114)	28.75 (33.12)	7.00 (3.54)	10.37	15.6
Florida (4/7)*	97 (39)	12.75 (2.17)	10.50 (1.66)	16.39	16.4
Wisconsin (3/3)	176 (46)	27 (0.82)	20.3 (2.6)	18.94	18

**The estimates include both systems used in the Florida site*

When comparing the observed and KLM measures for the entire MAR task, there are some interesting differences (Table 3). Arizona and Florida yielded a KLM measure estimate of 15.6 and 16.4 seconds while Wisconsin resulted in 18 seconds. These generally compared in line with the observed user times for Florida and Wisconsin with 16.39 and 18.94. However, in Arizona, the observed time was significantly shorter than the KLM estimated at 10.3 seconds, meaning the model over-estimated the required time to complete the MAR task. KLM does not take individual expertise and experience into account. For example, experience using a system can significantly reduce the visual search time. Notably, we observed that nurses could rapidly negotiate the screens and could anticipate where to click next with minimal search. The differences seen in Arizona and Florida are primarily due to the physical actions involved with the MAR task, while Wisconsin utilizes a different system, which required different steps overall. It should be noted that the sample is small and the variation is considerable.

To further explore the interaction complexities distinct users' face, clickstream data was collected for individual users and modeled on a timeline showing the series of clicks through task completion. The main goal of this visualization is to show variation across individual users. These can be seen in Figures 6, 7, and 8, showing clickstream data for Arizona, Florida, and Wisconsin. In Arizona, there are short occurrences that show a smaller amount of mouse clicks compared to other cases. This mainly shows that some instances require the clinician to document a single medication given at the time rather than an extensive series of medications. Similarly, there are cases with multiple occurrences of the MAR task, meaning that different medications were documented at different times resulting in discontinuities or fragmentation of workflow.

4.2.2 Clickstream Data

Based on the example of goals and subgoals expressed in Table 2, large clusters of activity (clicks) can be explicitly aligned to the subgoals and actions performed. For example, Figure 6 compares the clickstreams for multiple patient cases, a timeline of occurrences of mouse clicks throughout the cases. In Arizona case 2 (AZ2), there were many clicks between 10 and 47 seconds on the second instance of MAR. These clicks correspond to *Goal 2, Subgoal A: Select the Desired Medication.* The large number of clicks directly relates to the nurse trying to search through the extensive medication list, specifically the action of manually selecting the scroll button to navigate through the available medication list. This instance can be compared to Figure 6, Arizona case 11 (AZ11), where there were fewer clusters of clicks, meaning the nurse was more efficiently able to navigate the medication list within the MAR interface. This visualization not only allows for comparison of users across a single site but compare users across multiple sites.

In Florida, where the MAR process is overall more straightforward by requiring fewer mean mouse clicks, there are overall fewer clicks across users, as seen in Figure 7. There are still clusters of activities aligning with more involved subgoals and actions. In Figure 7, Florida case 1 (FL1), there is an initial burst of activity from 1 second to 20 seconds. This burst aligns with *Subgoal C: Save modified medication details*, where multiple actions are required to save the modified medication information within the MAR. In Figure 8, Wisconsin case 2 (EU2), there is a consistent stream of user clicks, primarily due to an entirely different system and process being utilized for the MAR task. The higher concentration of clicks seen in the second instance of Figure 8, Wisconsin case 2 (EU2) aligns with Goal 2 and both *Subgoal A, Document Medication "Start Time"* and *Subgoal B, Modify Personnel Details.* Overall, it was observed that users in Florida generally required fewer mouse clicks to complete the task because a different process is utilized, involving scanning medications rather than manually entering medication details. This process also resulted in shorter instances of the MAR task, although some of the time seen in the clickstream data for Florida can be attributed to lags in the system response.

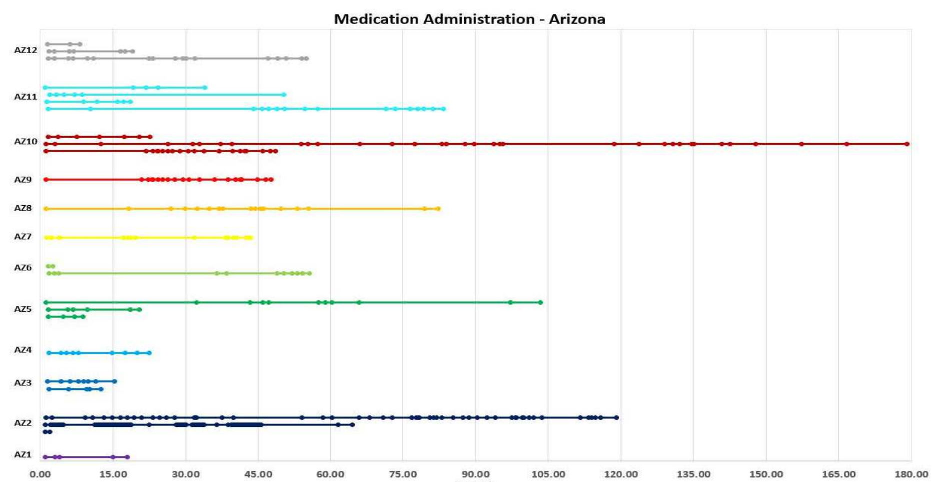

Figure 6: Clickstream data per user of the MAR task in Arizona. The x-axis represents time in seconds for task execution and the y-axis represents individual case instances. Multiple lines grouped together represent multiple instances of task occurrence. Each line represents an occurrence of the clinician performing the MAR task, where different colors represent different clinicians

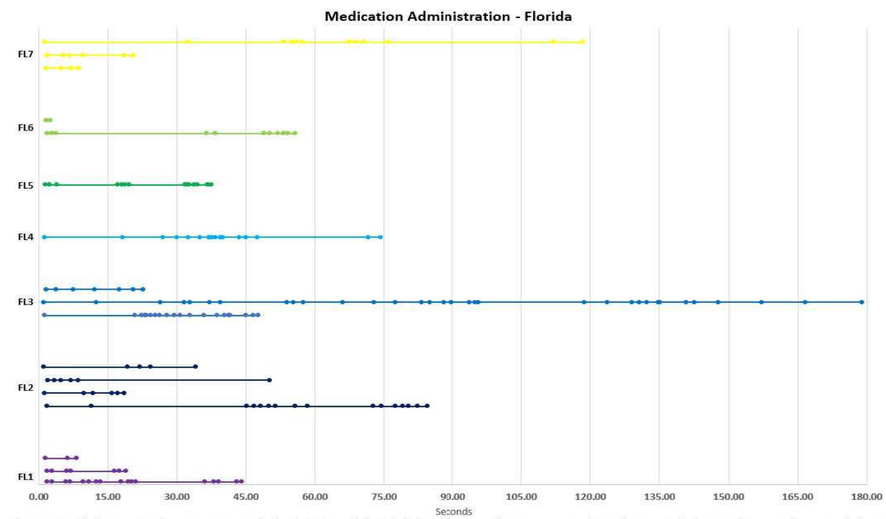

Figure 7: Clickstream data per user of the MAR task in Florida. The x-axis represents time in seconds for task execution and the y-axis represents individual case instances. Multiple lines grouped together represent multiple instances of task occurrence. Each line represents an occurrence of the clinician performing the MAR task where different colors represent different clinicians

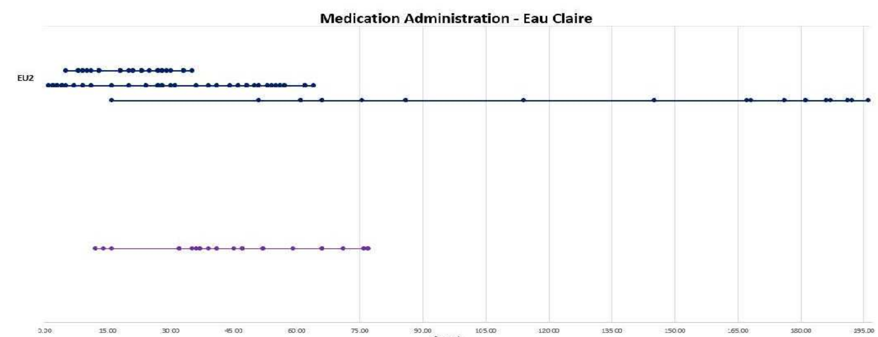

Figure 8: Clickstream data per user of the MAR task in Eau Claire. The x-axis represents time in seconds for task execution and the y-axis represents individual case instances. Multiple lines grouped together represent multiple instances of task occurrence.

5.0 Discussion

In this paper, we employed a navigational complexity framework to characterize differences in three EHR systems. Overall, SurgiNet required a shorter mean duration, fewer mouse clicks, and screen changes across all sites and systems. The overall ease of use and modes of interactions were generally simpler and required fewer perceptual-motor actions. Additionally, the fewer number of screen changes lessened the burden on working memory for users, thus reducing the overall cognitive load. Similarly, the clickstream data showed fewer mouse click activity between individual users and fewer dense clusters surrounding a specific part of the task. All pertinent actions to documenting medications were readily available in SurgiNet and more easily accessed than in the other two systems. The overall shorter occurrences of mouse clicks and goals from the cognitive walkthrough showed that the system facilitates clinicians to document single medications at a given time. In all three systems, there was a significant dependency on perceptual-motoric actions when navigating through the interface and locating the various fields for data entry, with specific emphasis being placed on SIS requiring higher number of overall complexities in navigation. Through analyzing the steps executed to complete the MAR tasks, complexities in EHR navigation were identified across different EHRs and clinical settings. These complexities were reflected by multiple measures, such as time spent on task, click counts, and screen transitions, and were found to influence nurses' performances. These complexities surfaced through tradeoffs in cognitive processes that mediate task performance.

The paper offers a theoretically grounded methodological approach for elucidating navigational complexity, a problem that was previously recognized as important but lacking in conceptual and methodological clarity. The study of navigational complexity benefits from a granular approach that captures the moment by moment experience of the user. The combination of quantitative and qualitative data offers a method of precision and higher reproducibility. The clickstream analysis, coupled with the walkthrough, enables segmentation of the sequential task process and user experience at the micro-analytic level needed to surface challenges that users encounter and characterize them in a meaningful way. It also extends the cognitive engineering framework which has informed EHR usability studies for 25 years (29).

One of the main strengths of this methodology is the use of multiple data streams to identify the impact that interface design elements have on EHR mediated workflow because together they provide a thorough understanding of the complexities involved with task completion (30,31). The comprehension of these user microstrategies provides a better understanding of the complexities users face in interacting with an interface, allowing for the tailoring and redesign of maximally optimal systems, promoting the most efficient and patient safety. There is a small, but steadily growing body of research comparing EHR systems (13,32,33) that can provide unique insights into the user experience and identify features that exemplify best practices, as well as those that do not meet that standard.

The novel approach described in this paper incorporates analytic measures, performed by analysts that focus directly on the elements of the interface and the task with measures of interactive behavior. It also employs constructs such as perceptual-motor activity, visual search, and working memory associated with different users' microstrategies, the series of individual steps to complete a task, which can lead to meaningful characterizations of interface complexity. Ideally, microstrategies provide the user with a way of optimizing interaction while minimizing the cost of that interaction, as reflected in measures of interactivity (14). The framework proposed here can be used to illuminate the nature of the design decisions and inform future design solutions at a granular level that stretches beyond other methods and frameworks. These tradeoffs are reflected in reduced screen transitions and minimizing memory load as reflected in both transitions between screens and screen clutter.

An advantage of cognitive engineering is its dual focus on elucidating the range of system complexities that can potentially impact cognitive performance using expert methods and the user strategies that enable practitioners to cope with these demands (13,29,34). The methods uncover different kinds of problems and when used in context, provide a richer multidimensional portrait of health information systems and user experiences (35). In recent times, innovative approaches have combined and extended these methods in novel ways to provide a more penetrating analysis of the user experience in healthcare contexts. In a related study, we examined the ways in which practitioner strategies compensate for the litany of EHR-mediated workflow problems including navigational complexity as it manifests itself across tasks (28,36).

Expert and user-based methods also complement one another because they capture the different kinds of constraints imposed by an EHR interface on navigational complexity. According to Fu and Gray, interactive behavior is determined by both hard and soft constraints (37). In many interactions with any application, there are hard constraints in which the interface determines the pattern of behavior. A clear-cut case is an ATM machine in which the sequence of steps needed to get cash is largely invariable (37). Similarly, there are subgoals in EHR-mediated tasks, for example engaging a dialogue box, which necessitates fixed patterns of behaviors and permits no degrees of freedom. Hard constraints should not be impacted by the host of variables such as case complexity that influence EHR-mediated workflow. Hard constraints can be described by expert-based methods. On the other hand, soft constraints in the interface suggest which of the possible patterns are likely to be chosen and executed but may afford considerable latitude (37). These can only be realized in user-based methods. Variation in the clickstream as evidenced in our results is indicative of users negotiating soft constraints. The pattern of behavior is subject to a range of influences beyond the interface including the individual differences of clinicians using an EHR.

The focus in this work is on EHR-mediated workflow and not exclusively on usability, although many methods common to usability studies were employed. Workflow is embedded in a more complicated process, which has temporal boundaries that stretch beyond task performance and even beyond the time frame of the PreOp nursing assessment. Designs are informed in part by dependencies between tasks or be a result of the availability or absence of information collected at an earlier point in time. It is not possible to judge an interface; instead, it needs to be understood in the context of other design choices and protocols driving the overall PreOp process. This can be achieved through user-modeling and clinical workflow simulations (31,38). A micro-analytic approach to modeling EHR-mediated workflow, as employed in this study, can help optimize HCI most effectively when used in the context of simulation. Differences in an interface can have rippling effects in workflow and affect task performance, specifically the time to complete a task. A better-designed interface can alleviate some of the burdens on working memory and thereby reduce the impact of the keyhole effect by enabling greater access to needed information on a given screen (9).

5.1 Limitations

There are several potential limitations. The study employed a small sample size and many factors impact workflow. However, the fusion of both expert review methods and user analysis allows greater confidence in the validity of these findings. Also, the study focused on navigating specific pathways to complete a task. It is a relatively finite problem space in that task completion is sequential (i.e., one goal or subgoal at a time) and there are only a small number of ways in which the task can be executed. In addition, a microanalytic approach enables us to cross-references subgoals derived from the walkthrough with clickstream data for a single clinician to identify task segments that are problematic. We can further characterize the problems in terms of interface elements employing a representational analysis and yield meaningful data with few participants. Recently, we have coupled this approach with process mining to explore large log file data sets which enable us to characterize thousands of events, albeit at a coarser level of granularity (39).

The use of the KLM method has limitations in relation to its precision (40). It was designed to model an expert path or workflow process. However, it is based on a small number of presuppositions for quantifying time to complete a task. It is unclear whether the specific tasks selected are the most important ones in the overall use of the EHR. It does not include the impact of expertise or experience, which can significantly impact performance. As such, it is a very useful, but not a sufficiently precise measure.

Another limitation is that the constructs of working memory and visual search were analyzed qualitatively in this paper. They can be quantified more precisely gauged by using eye-tracking methods (41,42). Although there are many challenges to collecting eye-tracking data in clinical settings, these data streams could greatly inform the measures, particularly as they relate to visual search.

Finally, the approaches described in this paper is rather labor-intensive, time-consuming, costly and necessitates substantial expertise to execute. It is also difficult to secure privileges to video record clinicians in live clinical settings. The framework describes an underlying theory, a set of measures and ways to conceptualize problems or features that result in complexity that extends beyond the specific measures used in this paper. Although we value the integrity of a more comprehensive granular approach, it is possible to employ this framework without engaging the full complement of data collection and methods of analysis.

6.0 Conclusions and Future Work

Navigational complexity has an undeniable impact on the burden experienced by clinicians when using an EHR. In this paper, we introduce a new methodological framework to model the navigation of EHR-mediated workflow. Different interfaces differentially mediate task performances, as reflected in interactive behavior. The analysis surfaced design tradeoffs. A future goal is to identify the suitable task-specific configuration of the EHR component parts (e.g., tables, widgets, search fields, dialogue boxes, etc.) that facilitate efficient performance and diminishes cognitive load. We anticipate designing and testing prototype or mockup interfaces that embody changes to an original design with the intent of reducing measurable navigational complexity.

We envision the navigational complexity framework with a reduced set of methods (e.g., emphasizing expert-review methods) being used as a practical tool to evaluate EHR task interfaces and to fashion human-centered design solutions. The framework can lead to evidenced-based small tractable changes that improve efficiency, streamline EHR-mediated workflow, and greatly enhance the user experience.

Future work could involve more precise quantitative modeling and the use of simulation methods to test different potential navigational trajectories. The micro-analytic approach necessitates scrutiny of a small number of subjects along with extending this framework to other clinical tasks, such as patient order management. The EHR-mediated workflow continues to present formidable challenges for users and developers. However, the growing body of work in the study of cognition and clinical workflow has the potential to yield insights and contribute instrumentally to the solution space for optimal design.

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8.0 Conflicts of interests

Drs. Richard Helmers, Karl Poterack, and Timothy Miksch are employees of the Mayo Clinic. None of the authors have conflicts to report.

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Appendix A: Cognitive walkthrough and KLM combination for the MAR task as completed in Florida

Goal 1: Navigate to Medication Administration Screen

Subgoal A: Locate the "Medication Administration" tab			
Action: Choose appropriate medication administration tab			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Visual Search Working Memory	Locate "Medication Administration" tab	M [Locate]	1.2
Subgoal B: Select "Medication Administration" tab			
Action: Click on "Medication Administration" tab			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Perceptual-Motor Visual Search	Point to "Medication Administration" tab	P [Point]	1.1
Perceptual-Motor	Click on "Medication Administration" tab	B [Mouse]	0.1
System Response: Generates "Medication Administration" screen			
Goal 2: Document medications			
Subgoal A: Enter medication details			
Action: Select appropriate medication			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Perceptual-Motor Visual Search	Point to appropriate medication	P [Point]	1.1
Perceptual-Motor	Click on appropriate medication	B [Mouse]	0.1
System Response: Generates medication details page			
Action: Physical scanning of medications			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Perceptual-Motor Working Memory	Scan distributed medication with barcode scanner	Ph [Physical]	2.0
System Response: Known medication details imported into medication administration screen			
Action: Select appropriate medication			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Working Memory	Determine the medication administration site	M [Locate]	1.2
Visual Search Working Memory	Locate "Site" section	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to "Site" section	P [Point]	1.1
Perceptual-Motor	Click on the "Site" section	B [Mouse]	0.1
Visual Search	Locate appropriate site	M [Locate]	1.2

Working Memory			
Perceptual-Motor Visual Search	Point to appropriate site	P [Point]	1.1
Perceptual-Motor	Click on appropriate site	B [Mouse]	0.1
Subgoal B: Save modified medication details			
Action: Select save sign button on "Medication Administration" screen			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Visual Search Working Memory	Locate the "OK" button	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to "OK" button	P [Point]	1.1
Perceptual-Motor	Click on the "OK" button	B [Mouse]	0.1
Visual Search Working Memory	Locate the "Sign" button	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to "Sign" button	P [Point]	1.1
Perceptual-Motor	Click on the "Sign" button	B [Mouse]	0.1
System Response: Pop-up screen saves medication details and cycles to next medication			

Goal 1: Navigate to Medication Administration Screen			
Subgoal A: Locate the "Preop Medications" Selection			
Action: Make selection from dropdown menu			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Visual Search Working Memory	Locate "Wizard Sets" dropdown	M [Locate]	1.2
Subgoal B: Select "PreOp Medications" Selection			
Action: Click on "PreOp Medications" Selection			
Perceptual-Motor Visual Search	Point to "Wizard Sets" dropdown	P [Point]	1.1
Perceptual-Motor	Click on "Wizard Sets" dropdown	B [Mouse]	0.1
Visual Search Working Memory	Locate "Preop Medications" choice	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to "Preop Medications" choice	P [Point]	1.1
Perceptual-Motor	Click on "Preop Medications" choice	B [Mouse]	0.1
Action: Select medication administration button			
Cognitive Process	Description	Operation	Time (Sec)
Visual Search Working Memory	Locate "Ortho Meds" choice	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to " Ortho Meds " choice	P [Point]	1.1
Perceptual-Motor	Click on " Ortho Meds " choice	B [Mouse]	0.1
System Response: Generates "Drug Administered" screen			
Goal 2: Document appropriate medications			
Subgoal A: Document medication "Start Time"			
Action: Modify medication start date/time			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Working Memory	Determine the date/time medication given	M [Locate]	1.2
Visual Search Working Memory	Locate the "Start Time" location	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to "Start Time" modification buttons	P [Point]	1.1
Perceptual-Motor	Click on the "Start Time" modification buttons to enter correct time	B [Mouse]	0.1

Visual Search Working Memory	Locate appropriate "Site" selection	M [Locate]	1.2
Subgoal B: Modify personnel details			
Action: Enter personnel details			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Visual Search Working Memory	Locate the personnel details section	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to the "Me" button of personnel details	P [Point]	1.1
Perceptual-Motor	Click on the "Me" button of personnel details	B [Mouse]	0.1
Subgoal C: Save modified medication details			
Action: Select save button on "Drugs Administered" screen			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Working Memory	Determine if all medication details entered	M [Locate]	1.2
Visual Search Working Memory	Locate the "Next" button	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to "Next" button	P [Point]	1.1
Perceptual-Motor	Click on the "Next" button	B [Mouse]	0.1
System Response: Pop-up screen saves medication details and cycles to next medication			

APPENDIX B

AMIA 2019 MEDREC STUDENT PAPER SUBMISSION

Navigational Complexities in Medication Reconciliation:
A Pre-Post EHR Conversion Comparison

Benjamin J. Duncan, MS[1]; David R. Kaufman, PhD, FACMI[1,2,*] ; Lu Zheng, RN, MHI[1]; Stephanie K. Furniss, PhD[1,2]; M. Adela Grando, PhD[1,2]; Karl A. Poterack, MD[2,4]; Timothy A. Miksch, MBA[2]; Richard A. Helmers, MD[2]; Bradley N. Doebbeling, MD, MSc[1,2,3]

[1] College of Health Solutions, Arizona State University, AZ, US;
[2] Kern Center Informatics and Knowledge Management, Mayo Clinic, Rochester, MN, US
[3] School for the Science of Healthcare Delivery, Arizona State University, AZ, US;
[4] Department of Anesthesiology, Mayo Clinic, AZ, US
***Senior Author**

Abstract

Medication reconciliation (MedRec) is a mission-critical task key to perioperative workflow. However, interface complexity within different EHR systems can result in poor usability, thus increasing the potential for adverse drug events and documentation burden. With a system-wide EHR conversion occurring at Mayo Clinic, we compared pre-post EHR interfaces to assess the impact on task performance. MedRec interfaces in pre-operative nursing assessments were compared and evaluated in three geographical regions using three different systems. Unnecessary navigational complexity contributed significantly to clinician's cognitive load, as demonstrated by differences in interactive behavior measures, workflow models and individual user data. Mean times per medication decreased from 6 seconds to 2.64 seconds pre-EHR conversion in Eau Claire and 12.05 seconds to 3.44 seconds pre-EHR conversion in Rochester. By applying a proposed navigational complexity framework, the impact of different EHR interfaces on task performance and usability barriers subsequent to a system implementation can be documented.

Introduction

A primary objective of human-computer interaction research in healthcare is to gain a clearer understanding of how health information technology (IT), specifically electronic health records (EHRs) facilitates or hinders clinical workflow (1). Interface complexity often results in poor usability of a system, resulting in overall dissatisfaction with EHRs and increasing safety challenges and burden of use (2). One significant recommendation of the AMIA 2020 task force was decreasing documentation burden (3). Poor usability contributes to the documentation burden problem. It can create barriers to clinical workflow due to lack of consistency across interfaces and systems and interactive complexities during data entry and navigation. EHR navigation difficulties result from having patient information scattered across multiple screens, unwieldy interfaces and data access and data entry processes that require a complex set of steps (4). By modeling the steps in clinical workflow and assessment of associated interfaces, areas with high cognitive load for clinicians and usability barriers and challenges can be further explored. An assumption guiding much work in this area is that small interface changes can significantly reduce bottlenecks in workflow and improve task performance (5). Comparative analyses can yield valuable insights into the sorts of changes needed to streamline navigation and enhance user performance.

Medication reconciliation (MedRec) is considered a vital process across healthcare settings and has a particularly important role before surgery. MedRec is the process of comparing a record of a patient's currently prescribed medications with a list of medications the patient has been actually taking to ensure the record is current and accurate. (6). Although the importance of the MedRec task is widely known, there is ample evidence to suggest that currently implemented systems often provide inadequate cognitive support to clinicians, presenting significant usability challenges and barriers (7). Often with the implementation of a new EHR, rate of the medication discrepancies during MedRec nearly doubles (7). These discrepancies can largely be attributed to interface design and variation of use in clinicians, often facilitated by system design. Currently, few studies compare the usability of various interfaces and system.

Several observational studies have identified interface complexities and the mediating effects that electronic MedRec systems have on patient safety and overall assess usability. The primary objective of these studies was to compare the MedRec task performance on different EHRs. Duncan et al. characterized EHR-mediated workflow prior to a system-wide EHR conversion comparing and evaluating the MedRec processes in two different EHRs. The interfaces were found to differ in modes of interaction and cognitive support based on specific interface design elements (7). A recent study by Horsky et al. compared the accuracy of two different electronic MedRec tools to determine the cognitive consequences associated with specific interface designs. It was found that significantly fewer errors were made in the EHRs with single column medication lists, as compared to using a system with side-by-side lists highlighting the need for MedRec tool usability testing and comparison tools for differing EHR interface designs (8). Plaisant et al. contrasted a conventional interface design with a novel design (Twinlist), using animations to split an interface versus an interface using side-by-side lists. Usability evaluations showed that Twinlist's multicolumn design facilitated the faster completion of MedRec with substantial reductions in the number of clicks (9). Tamblyn et al. designed and assessed the implementation of a new electronic MedRec tool to determine the optimal functionalities by assessing the time spent on the task. Required modifications to the interface was identified, reducing task completion time by nearly half (10). The variability in MedRec tools highlights the need for EHR usability comparison tools (11). There has been an observed increase in the number of providers switching from one EHR product to another (2). Through assessment and comparison of these systems, cognitive tradeoffs can be identified between different interface element designs, particularly, concerning working memory, visual search, and perceptual-motor activity.

We developed a navigational complexity framework to identify cognitive tradeoffs and challenges involved in EHR-mediated task completion. The framework leverages a range of cognitive engineering methods (12) and visualizations (11,13) to identify complexities within the system at a granular level and can be used to characterize individual users, interfaces and clinical sites (5). The framework was developed in service of the ROOT (Registry Of Operations and Tasks) project, an interdisciplinary team effort to document changes in clinical workflow at the Mayo Clinic as a result of a large-scale EHR conversion. One of the primary goals of the ROOT is to understand and interpret variation across different sites and systems (7,14). ROOT employs a broad range of methods including semi-structured interviews, log file analysis, and video ethnography to characterize EHR-mediated workflow in surgical settings. Grando et al. have leveraged this series of combined methods to understand variation in patient and provider EHR-mediated workflows and interactions within interfaces in the Mayo Clinic Phoenix preoperative (PreOp) setting (15).

The objective of our research is to understand EHR-mediated workflows and how the different facets of interface elements impact task performance and cognition. Task performance based on interface design is assessed by applying the navigational complexity framework to the pre-post implementation of a new EHR. This paper presents the application of this framework to a specific task that presents serious implications for efficiency and patient safety, MedRec.

Methods

The navigational complexity methodological framework is described in detail in Duncan et al. (5). Here we apply that framework for identifying the navigational complexities and variation across clinical sites and individuals. We apply two categories of analysis: expert-based and user-based methods to study navigational complexation in a MedRec task. Expert-based methods (e.g., representational analysis) mainly involve the evaluation and judgment of trained analysts. User-based methods rely on empirical data derived typically from observational or experimental studies. In this case, the observations were in-situ as nurses performed tasks prior to surgery.

Settings

Observations took place at two Mayo Clinic hospitals: the first one includes the Methodist and Saint Marys Campuses in Rochester, Minnesota and the second, the Eau Claire Hospital (Eau Claire, WI), which is part of the Mayo Clinic Health System. In this report, the Methodist and Saint Marys campus are combined due to their similar processes and geographical location. Results from Eau Claire and Rochester campuses are presented. The analysis was performed on video capture of 18 different patient cases involving 11 nurses across all sites.

Data Capture

The primary focus of data capture was on the preoperative (PreOp) nursing assessment performed by nursing staff in-situ on a variety of patients. Morae™ 3.3 video analytic software was used to capture workflow, where the software records the clinician's on-screen activities. The software also provides a set of analytics and audio and video recording of the clinicians' hands (e.g., use of paper documents, checklists) via a webcam. During data capture, an observer was also present to record notes and specific points of interest. The observer also employed a hand-held video camera and used it when permissible. Recordings were separated by patient cases across geographical locations. The patient case was the primary unit of analysis.

Data Analysis

Individual patient video recordings were reviewed for integrity and noticeable gaps in time (e.g., where no activity was observed), then were segmented into individual tasks based on an established clinical workflow task list. Once segmented, the specific task of interest was isolated, and data analysis was performed. The navigational complexity framework includes both expert-based and user-based analysis (5) on the MedRec task (Figure 1). Expert-based methods included representational analysis of interfaces to evaluate the appropriateness of representations for the given user performing a selected task (11) and process modeling to represent the idea sequence of steps involved in task completion. User-based methods such as interactive behavior measures and individual clickstream data for each clinician were used to understand what actions users performed and to identify and explain variation across users, systems and clinical sites. The data streams leveraged for this are shown in Figure 1, providing insight at a granular level. Figure 1A represents the manual coding of tasks from screen captures involved in the nursing assessment. The tasks are coded sequentially, and once segmented specific analytics are generated from the videos. The analytics, interactive behavior measures, were then converted to clickstream data, a timeline representation aiming to show variation and individual clicks involved with task completion presented in Figure 1B. When tasks are sequentially coded, a visualization to show the fragmentation of tasks and task switching frequency within EHR-mediated workflow was generated, shown in Figure 1C. This enables us to track multiple instances of tasks throughout PreOp.

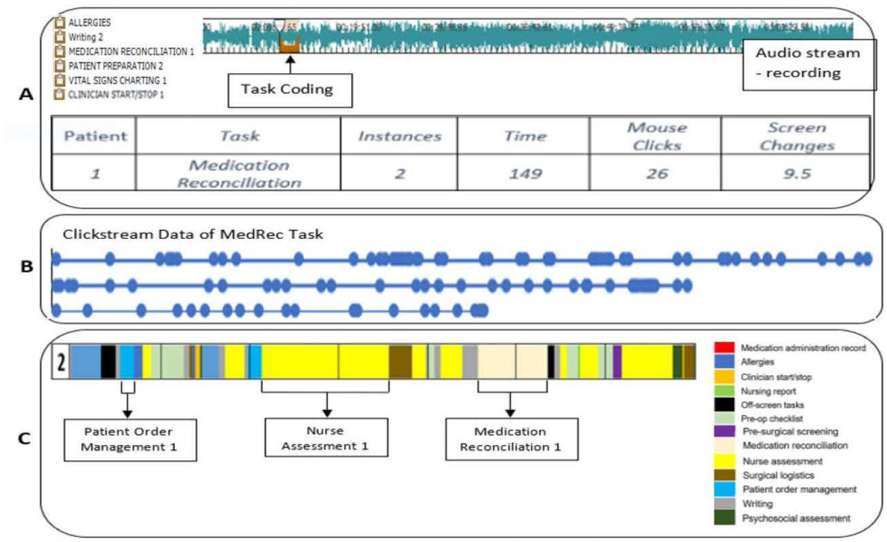

*Figure 1: Data streams for a single nurse and patient. **A** Morae video timeline with individual task coding and generated interactive behavior measure for the selected task. **B** Clickstream data for a single task for all instances. Each line represents a new instance or restart of the task and a single instance showing subgoals along the timeline of the task. Subgoals allow us to align clicks with different steps associated with task completion. **C** Time belt visualization showing selected tasks for a single visit. The visualization highlights the fragmentation or discontinuities in task completion.*

Results

We compared the MedRec task for two different EHRs (MICS LastWord and Epic) pre and post-conversion to a new EHR. Data was gathered from two different systems pre-EHR conversion: MICS LastWord in Rochester and Cerner PowerChart in Eau Claire. Post-EHR conversion was involved Epic at all sites. Figures 2 and 3 show schematic representations of the individual interfaces used to complete the MedRec task. Figure 2 represents MICS LastWord while Figure 3 represents Epic. Figure 2 shows a schematic representation of MICS LastWord MedRec interface and Figure 3 shows a schematic representation of Epic MedRec interface. In the surgical setting, this process is particularly important in that it ensures there are no reactions between prescribed medications and anesthesia while ensuring patients receive their prescribed medication during their hospital visit. The nurse caring for the patient completes the reconciliation process, and the date and time of the last dose taken by the patient. The date, time and if the medication is currently being taken are recorded.

Expert-based Methods – Representational Analysis

Pre-EHR conversion, the information documented is relatively uniform between the sites and systems; however the mode of interactions between the systems vary considerably. These interactive differences can be seen in the steps required to enter the last dosage of a medication. In Rochester, using MICS LastWord, a medication list is displayed on the screen, and to add the last medication dose, the "Add Last Dose Taken" button is selected, generating a pop-up screen to enter the date and time of the dose. The last date and time are entered, the "Continue" button is selected, and the entry is saved, closing the pop-up screen. This requires clinicians to utilize their working memory to recall what medication dosage is being entered, being that the pop-up window covers the medication list. However, there is less visual search required by engaging a pop-up window with the specific purpose of entering date/time. In Eau Claire, using Cerner PowerChart, there is a similar process for entering medication last doses. A medication list is displayed, and the desired medication is selected, and the user right clicks and selects "Add Last Medication Dose". Once selected, the screen splits into two different sections, showing the medication list and the compliance section where the last medication date and times are entered. This interface design requires more perceptual-motor activity however places less of an overall burden on working memory because the medication list is easily and readily visible. These interfaces vary in their mode of interactions compared to the post-Epic implementation, utilizing different functionalities in the MedRec interface where static buttons rather than drop-downs or dialogue boxes are used.

Post-EHR-conversion, in the Epic MedRec interface utilized at all campuses a medication list details the medication name, dosages for the medication and a series of static buttons that can be used for reconciliation of last medication doses. Thee static buttons are shown for each medication and when a dose is added into the system, the button detailing the last day of medication dose is selected and for the "Today" and "Yesterday" selections, a time is added and the checkbox under "Taking" is marked to indicate the medication is currently prescribed. Information regarding medications and the reconciliation functions are all easily visible and require a minimal amount of perceptual-motor activity. Once all medication doses are reconciled, the "Mark as Reviewed" button is selected saving all past medication doses as well as the user who completed the MedRec task.

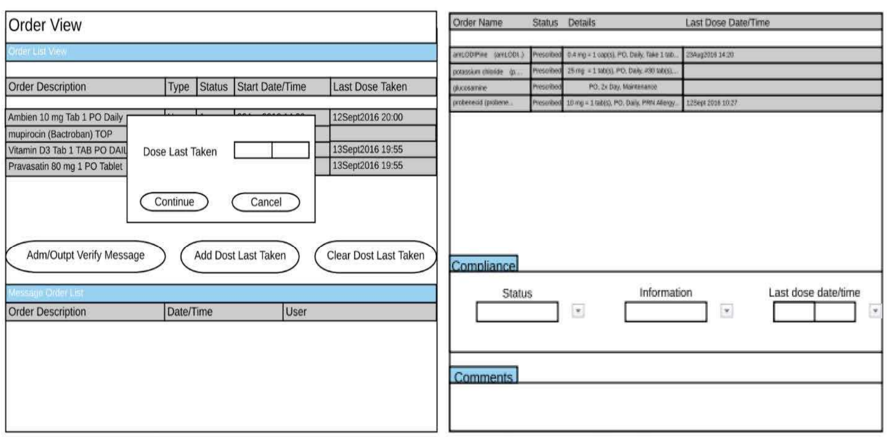

Figure 2: Medication Reconciliation interface used pre-EHR conversion in Rochester (left) and Eau Claire (right)

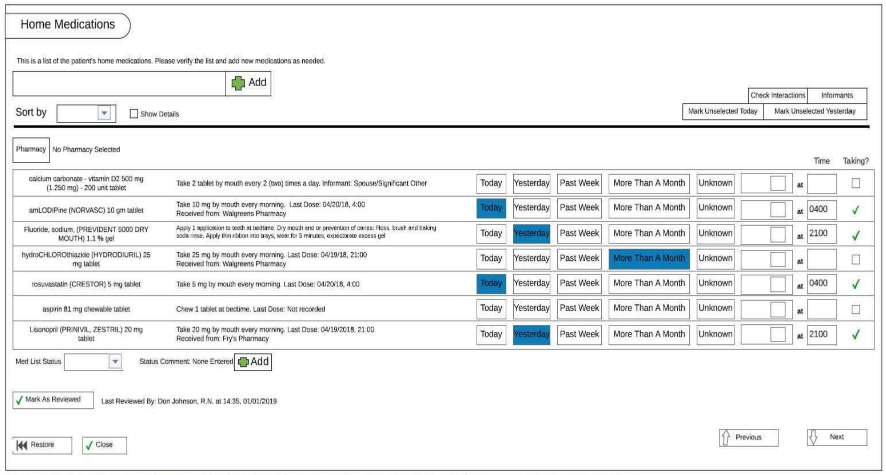

Figure 3: Medication Reconciliation interface used at both clinical sites post-EHR conversion

Expert-based Methods – Process Models

Figure 4 represents a process model for the Rochester pre-EHR conversion, Eau Claire pre-EHR conversion and post-EHR conversion steps involved with completing the MedRec task. The light black lines represent the process that occurs within all systems, the blue lines represent processes only in MICS LastWord, the red represents processes only in Cerner PowerChart, and the bold black represent steps only in Epic. In all systems, first, the nurse checks the paper admission medication list and must decide if the patient is currently taking medications. If no medications are currently being taken, the nurse signs off on the confirmed MedRec, and the process is over. After this decision, the systems pathways diverge. In MICS LastWord and PowerChart, the nurse must navigate to a separate screen to reconcile doses, while in Epic the last doses can directly be added on the initial MedRec interface. The appropriate medication is selected, and it is determined if this is a current prescription or not. In PowerChart and LastWord, this information must be searched for while in Epic, the information is readily available. Multiple actions are required in LastWord and PowerChart to actually add the last dose of medications involving different sections of the screen of pop-up windows. In Epic, reconciliation actions are directly available using static buttons. A final decision is made to determine whether all required medications have been reconciled before ending the process. Overall, it was found that the workflow facilitated by Epic required fewer steps to complete the MedRec task. Once the clinician determines if the medication is current, all reconciliation functionalities are readily available on the screen in Epic rather than requiring additional actions such as selecting an "Add Compliance" button as in PowerChart and LastWord. Because fewer actions are required, less overall time and interactive behavior measures are required to reconcile a single medication. The actions required for completing MedRec can be seen in bold black in Figure 4 below.

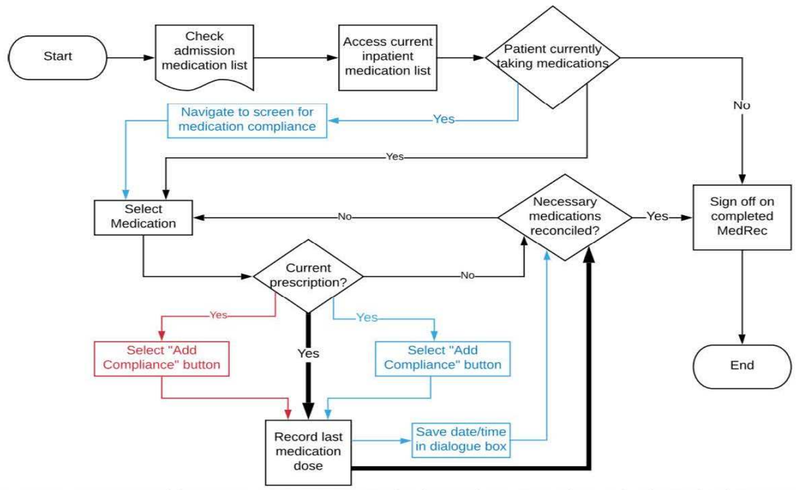

Figure 4: A process model representing the steps involved with completing the MedRec task. The thin black lines represent steps taken in all systems, the red represents PowerChart, the blue represents LastWord, and the bold black represents Epic

User-Based Methods Results

Table 1 presents the mean time and interactive behavior measures (mouse clicks and screen changes) for reconciling the last dose of a single medication dose. In Rochester, where MICS LastWord was used for pre-conversion MedRec, an average of 12.05 (1.91) seconds, 7.4 (2.5) mouse clicks and 4.2 (1.1) screen changes were required to reconcile a single medication dosage. This is compared to post-EHR conversion, using Epic, that required 3.4 (1.75) seconds, 1 (0.81) mouse clicks and 0 screen changes to reconcile a single medication. This can largely be attributed to the interface design changes where all reconciliation functions are readily available on the interface rather than requiring additional navigation. In Eau Claire, using PowerChart for MedRec, an average of 6 (0.2) seconds, 4.33 (0.47) mouse clicks and 1 (0) screen changes were required pre-EHR conversion to reconcile a single medication. This can be compared to post-EHR conversion, using Epic, that required an average of 2.64 (0.71) seconds, 1.5 (0.5) mouse clicks and 0 screen changes to reconcile a single medication. There was an overall reduction in time, mouse clicks and screen changes seen in the post-EHR conversion systems compared to pre-conversion systems.

Table 1: Mean time, mouse clicks and screen changes required for a single medication at the Eau Claire and Rochester sites

		Time per Medication (seconds)	Mouse Clicks	Screen Changes
Rochester – Pre N = 4	Mean	12.05	7.4	4.2
	SD	1.91	2.5	1.1
	Range	10-13.8	5 – 11	3 – 5
Rochester – Post N = 5	Mean	3.44	1	0
	SD	1.75	0.81	0
	Range	1.69 – 6.88	1 – 3	0
Eau Claire – Pre N = 4	Mean	6	4.33	1
	SD	0.2	0.47	0
	Range	6.3 – 6.7	4 – 5	1
Eau Claire – Post N = 4	Mean	2.64	1.5	0
	SD	0.71	0.5	0
	Range	1.79 – 3.54	1 – 2	0

By modeling individual users' clickstream data, interaction complexities users' face can be explored showing the series of clicks required for task completion and overall task efficiency. This visualization of user data has the primary goal of showing variation across individual users, systems and clinical sites. This clickstream data can be seen in Figure 5, showing the clickstream data for Rochester and Eau Claire pre and post Epic implementation. The x-axis represents a timeline for MedRec while each dot along the timeline represents one click performed by the user associated with completing MedRec. Clusters are indicative of a high density of clicks whereas segments of lines (i.e., periods) absent of clicks may reflect other activities such as visual search. In Rochester pre-EHR conversion, using MICS LastWord, there are more overall clicks required with higher clusters of clicks overall. This is facilitated mainly by requiring users to select the desired medication then click multiple buttons to generate the pop-up screen for the last dosage and saving details.

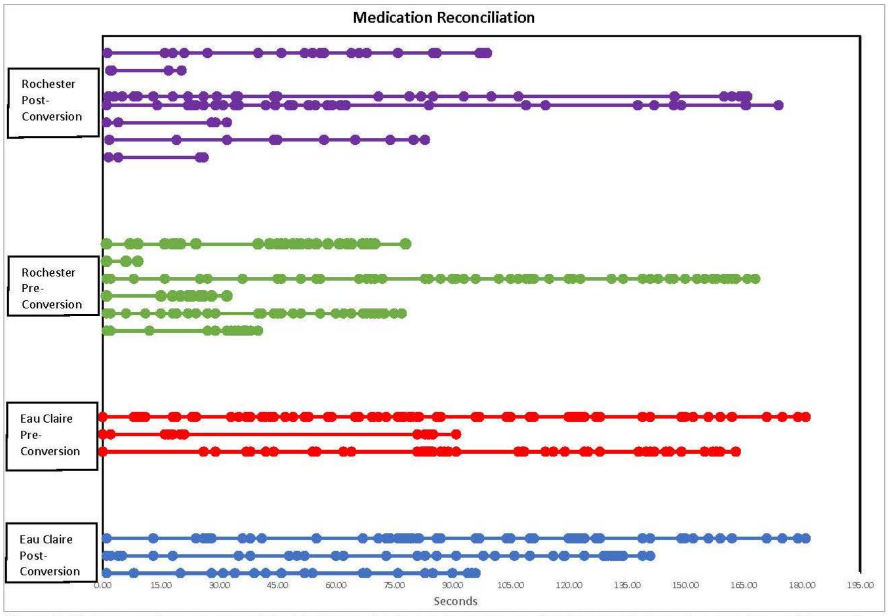

Figure 5: Clickstream data per user of the MedRec task. The x-axis represents time in seconds for task execution and the y-axis represents individual case instances. Multiple lines grouped together represent multiple instances of task occurrence. Blue represents post-EHR conversion in Eau Claire, Red represents pre-EHR conversion in Eau Claire, Green represents pre-EHR conversion in Rochester, and Purple represents post-EHR conversion in Rochester.

Discussion

The study documented changes to EHR-mediated workflow post-conversion as reflected in measures of interactive behavior. EHR conversion to different systems is increasing, which has a discernible impact on workflow and mission-critical tasks such as MedRec. Currently, there are substantial challenges to comparing EHRs (2) and few frameworks to inform the usability comparison (11), resulting in a lack of information to guide new EHR selection decision-making (2,16). This paper aimed to contrast the EHR-mediated workflow and how interface design can affect navigational complexity and task efficiency. The process of MedRec across three tertiary charting systems (from two Mayo Clinic hospitals) pre and post new EHR implementation were compared through the application of the navigational complexity framework. We observed differences in modes of interaction as mediated by small differences in interface design. The new system, Epic, utilized an overall more straightforward interface, consisting of a single screen that supported a range of actions.

We observed a shorter mean duration, fewer mouse clicks and screen changes per medication during the MedRec task post-implementation. When compared to the pre-implementation system, ease of access to the MedRec interface and the modes of interactions were generally simpler and required fewer perceptual-motor actions. Also, the fewer screen changes also lessened the burden on working memory for users, thus reducing the overall cognitive load. This was also evidenced in the clickstream data, showing fewer mouse clicks activity of individual users and fewer dense clusters surrounding a specific part of the task. All medications pertaining to the patient are readily available in Epic with dosage information and actions related to reconciling last medication doses are readily available compared to the pre-implementation systems (PowerChart and LastWord) required multiple actions to access the medication dosage functionalities. In the context of the nurses' work, the most recent home medication list is reviewed with the patient and patient provide the last time the medication was taken; however, in PowerChart and SurgiNet the compliance section is not readily available, requiring additional navigation, burdening working memory of the nurses to enter medication details, while Epic has all compliance actions available without additional navigation required. On the other hand, a more complicated case than observed in the study may result in greater visual search and scrolling.

Differences in navigation and interface design contribute to poor task efficiency. Providers often perceive EHRs as difficult to use, and usability analysts have cited issues with difficult-to-read interfaces, confusing displays, and iconography that lacks consistency and intuitive meaning (17). These usability issues can often lead to increased cognitive load. These challenges may surface when transitioning from one system or interface to another, causing disruptions to workflow and efficiency (18,19). By applying the navigational complexity framework, we can better understand how different EHR interfaces differentially mediate task performance and document changes after system implementation. This also allows for a deeper understanding of task complexities at a more granular level.

There are several limitations to this work. The study employed a small sample size, and there are many uncontrollable factors that can have an impact on EHR-mediated workflow. However, by applying the navigational complexity framework leveraging both analytic methods and user analysis, we can validate and even anticipate some of the findings. The modeled pathways represent the most commonly observed rather than a complete set of possible trajectories. In addition, we cannot conclude that one EHR is superior to another for the task of medication reconciliation. Clearly, there are other factors such as decision support that were not considered here. However, we can reasonably assert that reduced navigational complexity can alleviate some of the documentation burden issues and enhanced user experience.

Notably, however, EHR navigation for a given task is a relatively finite space, and there are a small number of routes to task completion. Future work involves extending this framework to additional clinical tasks within the nursing assessment and to other clinical settings and roles. We are beginning to explore how we can contribute to the solution space in efforts to streamline re-design and reduce cognitive load. We have successfully applied this navigational complexity framework to the task of MedRec in this paper and the task of vital signs in our previous work (5), demonstrating the extensibility of the framework. In our previous studies, we have also employed expert-based methods including the cognitive walkthrough and keystroke-level modeling (KLM) to study navigational complexity. This enables us to quantify the complexity of the interaction in more precise terms. We are in the process of applying these methods to MedRec and other tasks. With the triangulation of different data sources such as log files for data mining, the small sample size can be supplemented with supporting data streams (15) to characterize broader patterns of interface navigation across clinicians and over time.

Conclusions

Use of a navigational complexity framework helped identify interface design differences and how they can contribute to cognitive load and documentation burden. Expert-based and user-based analyses were applied to the MedRec task to better understand usability barriers at a more granular level and their effect of task performance and efficiency. The analyses completed in this paper identified interface design elements that differentially mediate task performance. By establishing system comparison tools to identify potential usability barriers in a system, issues can be identified with the goal of enhancing the user experience, leading to a higher quality of care in workflow while informing optimization efforts.

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APPENDIX C

AMIA 2020 PATIENT ORDER MANAGEMENT STUDENT PAPER SUBMISSION

We're Lost, But We are Making Good Time: Navigating Complex Pathways in a Patient-Order Management Task

Benjamin J. Duncan[1], Alexandra N. Kassis[1], David R. Kaufman*[5], Adela Grando[1], Karl A. Poterack[2,4], Rick A. Helmers[2], Timothy K. Miksch[2], Lu Zheng[1], Bradley N. Doebbeling[1,3]

[1] College of Health Solutions, Arizona State University, AZ, US;
[2] Kern Center Informatics and Knowledge Management, Mayo Clinic, Rochester, MN, US
[3] School for the Science of Healthcare Delivery, Arizona State University, AZ, US;
[4] Department of Anesthesiology, Mayo Clinic, AZ, US
5 Medical Informatics, SUNY Downstate Health Sciences University, Brooklyn, NY

***Senior author**

Abstract

Patient order management (POM) is a mission-critical task for perioperative workflow. Interface complexity within different EHR systems result in poor usability, increasing documentation burden. POM interfaces were compared across two systems prior to (Cerner SurgiNet) and subsequent to an EHR conversion (Epic). Here we employ a navigational complexity framework useful for examining differences in EHR interface systems. The methodological approach includes 1) expert-based methods—specifically, functional analysis, keystroke level model (KLM) and cognitive walkthrough, and 2) quantitative analysis of observed interactive user behaviors. We found differences in relation to navigational complexity with the SurgiNet interface displaying a higher number of unused POM functions, with 12 in total whereas Epic displayed 7 total functions. As reflected in all measures, Epic facilitated a more streamlined task-focused user experience. The approach enabled us to scrutinize the impact of different EHR interfaces on task performance and usability barriers subsequent to system implementation.

Introduction

A primary objective of human-computer interaction research in healthcare is to gain a clear understanding of how health information technology (IT) facilitates or hinders clinical workflow, specifically within EHR use (1). Complexity within an interface often results in poor usability of a system, generating barriers to efficient workflow. There is universal dissatisfaction with electronic health records (EHRs), specifically increasing safety challenges and burden of use (2). One significant recommendation of the AMIA 2020 Task Force was decreasing documentation burden (3), of which poor system usability can significantly contribute. This poor usability can create barriers to clinical workflow due to a lack of consistency across interface design, generating interaction complexities during data entry and navigation. Inefficient EHR system navigation can result from having patient information scattered across multiple screens, unwieldy interfaces, and data access and data entry processes that require a complex set of steps (4). By modeling the steps in clinical workflow and assessment of associated interfaces, areas with high cognitive load and usability barriers and challenges can be further explored. An assumption guiding much of the work in this area is that small interface changes can significantly reduce bottlenecks in workflow and improve task performance (5). Comparative analyses can yield valuable insights into the sorts of changes needed to streamline navigation and enhance user performance (6).

The objective of our research is to understand EHR-mediated workflows and how the different facets of interface elements impact task performance and cognition. Task performance based on interface design is assessed by applying the navigational complexity framework to the pre-post implementation of a new EHR while comparing used and unused interface elements. This paper presents a comparison of the different EHR interface design elements. It analyzes their frequency of use in clinical workflow and how these design elements influence task performance and efficiency.

Background

Healthcare institutions have invested significantly in the implementation of new EHRs. The expectations that EHRs will enhance productivity and streamline workflow have met with equivocal results. The persistent problem is that EHR interface designs are frequently unnecessarily intricate, compromising the user experience (8). There is a myriad of factors that contribute to the usability challenges experienced by clinicians. Some of them, for example, policies mandating increasing volumes of documentation, are beyond the scope of human-computer interaction research. However, there has been a growing body of research that has expanded the range of usability research and situated within the broader spectrum of EHR-mediated workflow (2, 7, 9). Recent efforts have been made to characterize, operationalize, and reduce navigational complexity (4, 5). EHR-based navigation can be construed as an interaction with user interface presentation and controls that allow users to locate and access needed information(4). Navigation describes the path taken to complete a task, including the actions (e.g., mouse clicks) and the traversal through space (e.g., negotiating a sequence of screens) (5). In this paper, we employ a cognitive engineering (CE) framework for the development of principles, methods, and tools used to assess and guide the design of systems to support human performance (10). User behavior can be characterized as a combination of elementary cognitive, perceptual, and motor behavior(11). Certain task-system combinations may be more memory-intensive, or, require more in the way of perceptual and motor behavior (11). Problematic navigation creates significant cognitive overhead with efforts devoted to managing the interface and fewer resources available for completion of EHR-mediated clinical tasks.

The study reported in this paper builds on our prior research into task-based navigational complexity. Duncan and colleagues studied vital signs documentation, medication reconciliation, and medication administration record tasks in the EHR, characterizing how different charting interfaces mediate performances across clinical sites (5, 12, 13). The study documented how the configuration of interface elements created unnecessary complexities when interacting with the system, as reflected in time on task and interactive behavior complexity measures. Based on this work, Duncan et al. developed a navigational complexity theoretical and methodological framework for examining differences in EHR interface systems and their impact on task performance (5). The framework employs both expert review and user testing methods to explore differences in task-specific EHR interfaces. The approach also draws on Calvitti et al., which applied methods for capturing, analyzing, and visualizing EHR use and clinical workflow (7). We also incorporate techniques from the TURF EHR usability framework, which operationalize and explains usability differences employing a range of methods (8). Specifically, we draw on a functional analysis approach to categorize the relative instrumental value of interface elements (realized as functions) in completing a task (14).

Methods

The navigational complexity methodological framework is described in detail in Duncan et al. (12). In this paper, the mentioned framework is applied in the process of identifying the complexities in navigation variation across clinical sites and individuals. There are two main categories of analysis: expert-based methods (e.g., representational analysis) mainly involve the evaluation and judgment of trained analysts. User-based methods rely on empirical data derived typically from observational or experimental studies. In this case, the observations were in-situ as nurses performed tasks before surgery. The Registry of Operations and Tasks (ROOT) Project was launched to characterize current workflows focusing on EHR use in the surgical services department. One of the primary goals of the ROOT is to understand and interpret variation across different sites and systems.

Settings

Observations took place at four Mayo Clinic hospitals: Phoenix, AZ, Rochester, MN, Jacksonville, FL, and Eau Claire, WI. The analysis was performed on video capture of 18 different patient cases involving 11 nurses across all sites. At the Arizona and Florida campuses, the primary tool used for charting was Cerner SurgiNet. . A total of 14 hours of video recordings were captured across 11 different nurses over 10 days at the three different clinical sites, which are presented in this work The primary focus of data capture was on the preoperative (PreOp) nursing assessment performed by nursing staff in-situ on a variety of patients. Morae™ 3.3 video analytic software was used to capture workflow, where the software records the clinician's on-screen activities.

Data Analysis

Video recordings of individual patient encounters were reviewed for integrity and noticeable gaps in time then were segmented into different tasks based on an established clinical workflow task list. Once segmented, the specific task of interest was isolated. The navigational complexity framework applied here includes both expert-based and user-based analysis (5) on the POM task. Expert-based methods included representational analysis of interfaces to evaluate the appropriateness of representations for performing a selected task (11) and process modeling to represent the ideal sequence of steps involved in task completion. User-based methods such as interactive behavior measures for each clinician were used to understand what actions users performed and to identify and explain variation across users, systems, and clinical sites. Functional analysis was performed to gain a thorough understanding of the functionalities that are required to meet specific work requirements (TURF). User interface elements were categorized as objects or operations and situated within the task completion where each function was utilized.

Results

We compared patient order management documentation across two different systems: Cerner (SurgiNet), which was the legacy system, and the newly implemented Epic system. Schematic representations of the interfaces used for patient order management in SurgiNet and Epic are presented in Figures 1 and 2. In the surgical setting, this is a particularly important task as no processes involving patient care can be completed unless an order is entered for that process. The method of managing patient orders includes activating and deactivating orders for execution, releasing orders from holding for various clinical tasks, and creating verbal orders for emerging tasks for specific patients that need to be completed. The results are organized as follows: schematic representations of the interfaces used in POM to provide a visualization of the interface elements, an excerpt from a cognitive walkthrough/KLM to show the goals, actions and cognitive processes of task completion, a workflow model aligning goals and subgoals with the used functions and interactive behavior measures showing the perceptual-motor effort required from users.

Interface Schematic Representation Descriptions

Figures 1 and 2 present schematic representations of the individual interfaces used to complete the POM task. There is a general universal protocol for releasing and activating orders across all surgical settings. However, the process in which these steps are completed varies substantially across systems. In Cerner SurgiNet, there was a menu column that allowed for navigation between various sections of the EHR, and one of the available options was the "Orders-Charges" tab. Information was displayed in a list form with the ability to shift between various sections of orders through a navigation pane (see Section A, Figure 1). Active outstanding orders were displayed in bold. Although the steps involved in task completion are nearly identical, there are differences in the representations of orders, in particular, the headers used to categorize orders. Epic presents a significantly smaller number of available functions when accessing the POM interface. There is a menu column that allows for navigation between various sections of the EHR. One of the main options is the "Orders" button, as seen in Figure 2 Section A. Information was displayed in list format with the ability to sort orders into labeled sections such as "Signed and Held" (see Section B, Figure 1).

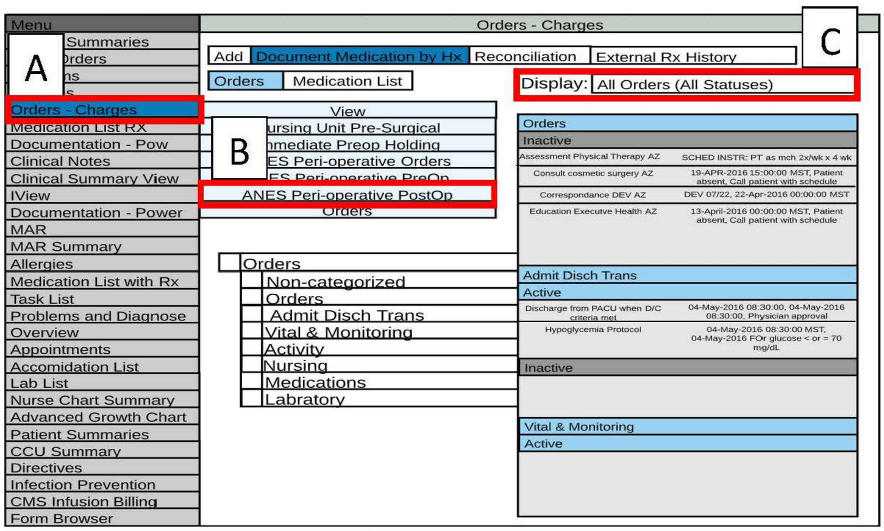

Figure 1: Schematic representation of the POM interface presented in Cerner SurgiNet

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When comparing the different functions available within the two different systems, there are variations between the different modes of interactions as well as the available functions within the interface. Cerner SurgiNet has a more significant subset of functions available when navigating through the system to the POM interface that is not related to the task of focus. These can be seen in Figure 1, where a total of 29 functions are available in the left-hand panel, covering a range of tasks, including POM. The multitude of elements likely increases the visual search for the user when navigating to the needed function and adding more steps to complete a task. Epic has a much higher ratio of overall used functions relative to those visible, where a total of 10 functions are initially available to users to navigate to the POM interface, as seen in Figure 2 Section A. In both SurgiNet and Epic, these functions are static buttons. When navigating to the appropriate section of orders, there are numerous different functions within SurgiNet that users have access to, 16 in total. Although these are used for categorization and sorting, clinicians uniformly employ one function, as seen in Figure 1 Section B. All of these functions are either checkboxes or dropdown selections. There is a more significant visual search effort required for users to locate the correct function. In Epic, there are a total of 7 different selectable functions when navigating to the appropriate section of orders. The available functions provide a narrower subset of options, making task completion more streamlined, as seen in Figure 2 Section B. During the process of activating and releasing orders, SurgiNet offers several different available functions within the interface that are pertinent to the task but not utilized. In Epic, there is an overall smaller subset of functions available to users within the interface for activating orders. By restricting the displayed functions, there is a more streamlined workflow that makes the overall process simpler but at the expense of not having proximal access to other desired functions.

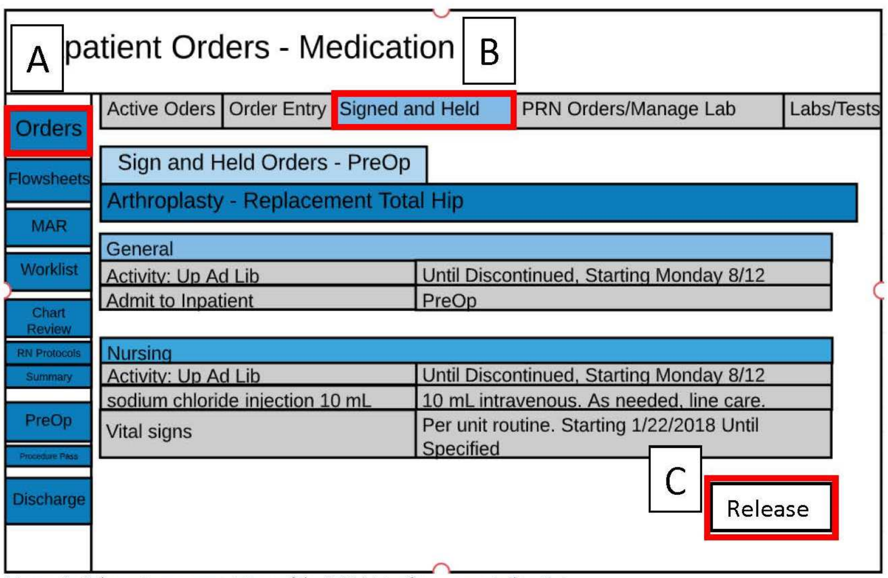

Figure 2: Schematic representation of the POM interface presented in Epic

Cognitive Walkthrough

To efficiently interact with the functions on-screen to complete the task, clinicians need to situate the process as goals and subgoals with associated actions and cognitive processes. While there are physical actions (mouse clicks), these do not show the complexities involved with task completion. To understand these complexities and how functions influence the cognitive processes, a combination of a cognitive walkthrough and KLM was created to show the goal and actions required to complete the POM task, as seen in Tables 1 and 2. The purpose of this analysis was to use the cognitive walkthrough to show the milestones of task progress and then leverage the KLM to model the physical and mental actions taken by users to reach these milestones. Additionally, cognitive processes were also aligned with these actions that correspond with the functions used for task completion. Table 1 shows a portion of a primary goal, subgoals, actions, and cognitive processes associated with POM. Being that the methods are mostly identical for all sites, this table reflects the general procedure with slight variations existing for site-specific details. The primary goal of all systems was to navigate to the appropriate interface and activate applicable patient orders.

Table 1: Combination of KLM and Cognitive Walkthrough for the Patient Order Management Task in Cerner SurgiNet

Goal 2: Activate Appropriate Order sets			
Subgoal A: Locate Appropriate Section of Orders			
Action: Search Header options for the "Signed and Held" section			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Working Memory	Decide what order section is appropriate	M [Locate]	1.2
Visual Search Working Memory	Locate the "Signed and Held" section	M [Locate]	1.2
Subgoal B: Select "Signed and Held" section			
Action: Click on "Signed and Held" section			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Perceptual-Motor Visual Search	Point to "Signed and Held" section	P [Point]	1.1
Perceptual-Motor	Click on "Signed and Held" section	B [Mouse]	0.1
System Response: Show all Orders in section			
Subgoal C: Determine Appropriate Orders for Patient			
Action: Select appropriate order sets to release			
Cognitive Process	Description	Operation	*Time (Sec)*
Visual Search Working Memory	Locate the order sets to release	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to the checkbox of the order set to release	P [Point]	1.1
Perceptual-Motor	Click on the checkbox of the order set to release	B [Mouse]	0.1
Perceptual-Motor Visual Search	Point to the "Release" button	P [Point]	1.1
Perceptual-Motor	Click on the "Release" button	B [Mouse]	0.1
System Response: Ordered released to be executed			
Subgoal D: Activate Appropriate Orders			
Action: Select Orders to Activate			
Cognitive Process	Description	Operation	Time (Sec)
Visual Search Working Memory	Locate the orders order section to activate	M [Locate]	1.2
Perceptual-Motor	Point to order section to activate	P [Point]	1.1

Visual Search			
Perceptual-Motor	Click on order section to activate	B [Mouse]	0.1
Visual Search Working Memory	Locate "Activate" button	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to "Activate" button	P [Point]	1.1
Perceptual-Motor	Click on "Activate" button	B [Mouse]	0.1
System Response: Activated list of orders for review			

For SurgiNet, in goal 2, activating appropriate orders, there are a total of 5 different subgoals used as milestones. Subgoals A-D requires that the user perform one action while subgoal E requires two separate actions by the user to complete. Each of the steps associated with a subgoal involves a series of cognitive processes, however, there is no uniformity between these processes. Subgoal D and E are the most complex with 6 steps involved in each of the actions for both subgoals. Although Subgoal D requires one action, subgoal E required 2 separate actions. There was considerable visual search, dependence on working memory, and extra perceptual-motor activity associated with these steps. Once this was completed, the remaining steps were consistent across all sites where orders were identified for signature. For Epic, in goal 2, activating appropriate orders, there are a total of four subgoals used as milestones for task completion. Subgoal D is the most complex with 1 action, however, there are multiple steps involved in this action, 6 in total, and several cognitive processes. The most prominent are visual search and perceptual-motor activity.

Table 2: Combination of KLM and Cognitive Walkthrough for the Patient Order Management Task for Epic

Goal 2: Activate Appropriate Orders			
Subgoal A: Locate Appropriate Section of Orders			
Action: Search Header options for the "SURG General PreOp AZ" Section			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Working Memory	Decide what order section is appropriate	M [Locate]	1.2
Visual Search Working Memory	Locate the "SURG General PreOp AZ" section	M [Locate]	1.2
Subgoal B: Select "SURG General PreOp AZ" Section			
Action: Click on "SURG General PreOp AZ" Header			
Cognitive Process	*Description*	*Operation*	*Time (Sec)*
Perceptual-Motor Visual Search	Point to "SURG General PreOp AZ" section	P [Point]	1.1
Perceptual-Motor	Click on "SURG General PreOp AZ" section	B [Mouse]	0.1
System Response: Show all Orders in section			
Subgoal C: Determine Appropriate Orders for Patient			
Action: Search Order Set for Relevant Orders			
Cognitive Process	Description	Operation	*Time (Sec)*
Working Memory	Decide what order appropriate to activate for patient	M [Locate]	1.2
Visual Search Working Memory	Locate the orders to activate	M [Locate]	1.2
Subgoal D: Activate Appropriate Orders			
Action: Select Orders to Activate			
Cognitive Process	Description	Operation	Time (Sec)
Visual Search	Locate the orders order section to activate	M [Locate]	1.2

Working Memory			
Perceptual-Motor Visual Search	Point to order section to activate	P [Point]	1.1
Perceptual-Motor	Click on order section to activate	B [Mouse]	0.1
Visual Search Working Memory	Locate the "Activate" button	M [Locate]	1.2
Perceptual-Motor Visual Search	Point to "Activate" button	P [Point]	1.1
Perceptual-Motor	Click on "Activate" button	B [Mouse]	0.1

Navigations Paths

Figure 3 shows a sunburst diagram of the different interface design functions hierarchy SurgiNet (blue) and Epic (green) require. Each section where the layout expands shows where the user would navigate to get to the POM interface. When interacting with the system, there are several interactive behaviors and cognitive processes involved in task completion. When completing the individual steps and procedures, there are different interface functions within the EHR that users interact with and navigate through to complete the task. Users go through a hierarchy of functions to get to their desired interface, with different systems having different navigational hierarchies. Bother Cerner SurgiNet and Epic have three levels of navigation to get to the desired interface. However, the SurgiNet system requires users to navigate through a higher number of unused functions, with SurgiNet displaying 12 different functions while Epic displays 7 functions overall. This shows that although the number of steps to navigate through the interface is similar, the cognitive effort to navigate through these interfaces is different.

Figure 3: Sunburst diagram for Cerner SurgiNet (blue) and Epic (green)

Interactive Behavior

Tables 3 and 4 represent the different interactive behavior measures (mouse clicks, screen changes) that are required by a user when completing the POM task in the pre-implementation system across various clinical sites, all using the same system. These measures show average values across users. These measurements provide some insight into the effort required by users to complete a task as well as task performance to quantify better the burden of navigational complexity placed on clinicians. The functionalities and navigation were nearly identical, with only the presentation of data varying. KLM showed that Arizona required 20.1 seconds, Florida required 23.57, and Eau Claire required 15.61 seconds, respectively.
In contrast, KLM ranged from 20.1 seconds for Arizona, 16.8 seconds for both Florida and Eau Claire. As mentioned above, Arizona required additional steps in the second action of subgoals E, yielding a higher KLM value than elsewhere. This resulted in a higher amount of mouse clicks, 61.4, while Florida and Eau Claire required 12.67 and 7.0 to complete POM. Arizona and Eau Claire observed versus KLM times mostly aligned, while there was a significant difference in Florida observed versus KLM times. In Florida, nearly one-fifth of the observed time was spent waiting for the system to load and populate the screen with patient information, accounting for the difference between the observed and KLM. Table 4 shows mean values for time, mouse clicks, screen changes, and the noted times for Epic in comparison.

Table 3: Patient Order Management summary of Interactive Behavior measures, the KLM predicted task duration and the actual task duration for Cerner SurgiNet

Location (Task completed/ All cases)	Mean (SD) of Time (sec)	Mean (SD) of Mouse Clicks	Mean (SD) of Screen Changes	KLM
Arizona (6/8)	198 (138)	61.4 (47.72)	18.6 (11.9)	20.4
Florida (4/7)	98 (59)	12.67 (13.67)	9.00 (8.49)	16.8
Eau Claire (3/3)	36 (29)	7.0 (5.1)	4.5 (3.0)	16.8

Table 4: Patient Order Management summary of Interactive Behavior measures, the KLM predicted task duration and the actual task duration for Epic

Location (Task completed/ All cases)	Mean (SD) of Time (sec)	Mean (SD) of Mouse Clicks	Mean (SD) of Screen Changes	KLM
Arizona (6/8)	46.25 (49.72)	6.75 (3.63)	3.5 (1.65)	9.6
Florida (4/7)	35.8 (14.4)	9.33 (3.2(	5.3 (2.0)	9.6
Eau Claire (3/3)	28.02 (5.24)	6.2 (2.6)	2.2 (1.37)	9.6

Discussion

The study documented changes to EHR-mediated workflow post-conversion as reflected in measures of interactive behavior. EHR conversion to different systems is increasing, which has a discernible impact on workflow and mission-critical tasks such as POM. Currently, there are substantial challenges to comparing EHRs (2) and few frameworks to inform the usability comparison(14), resulting in a lack of information to guide new EHR selection decision-making (2). This paper aimed to contrast the EHR-mediated workflow and how to interface design, including the distribution of functional elements, can affect navigational complexity and task efficiency. The process of POM across two charting systems from Mayo Clinic hospitals were compared through the application of the navigational complexity framework. We observed differences in modes of interaction as mediated by differences in interface design.Epic utilized an overall more streamlined interface, consisting of a more focused and task-centered approach with fewer functional options available that were not directly associated with the POM task.

We observed a shorter mean duration, fewer mouse clicks, and screen changes per order during the POM task post-implementation. When compared to the pre-implementation system, ease of access to the POM interface and the modes of interactions were generally more straightforward and required fewer perceptual-motor actions. Also, the fewer screen changes lessened the burden on working memory for users, thus reducing the overall cognitive load. This was also evidenced in the functional analysis and the sunburst representation, indicating a higher ratio of task-centered functions. The cognitive walkthrough revealed that fewer subgoals were necessary to achieve the goals of activating order sets in Epic relative to SurgiNet. The KLM analyses also predicted a substantial difference of almost 15 seconds to navigate and enable a single order. The convergence of different data analyses incorporating expert and user data suggests that these differences may be robust, even given the small sample size.

Differences in navigation and interface design contribute to poor task efficiency. Providers often perceive EHRs as challenging to use, and usability analysts have cited issues with difficult-to-read interfaces, confusing displays, and iconography that lacks consistency and intuitive meaning(1). These usability issues can often lead to increased cognitive load. These challenges may surface when transitioning from one system or interface to another, causing disruptions to workflow and efficiency (15). By applying the navigational complexity framework, we can better understand how different EHR interfaces differentially mediate task performance and document changes after system implementation. This also allows for a deeper understanding of task complexities at a more granular level.

There are several limitations to this work. The study employed a small sample size, and many uncontrollable factors can have an impact on EHR-mediated workflow. However, by applying the navigational complexity framework leveraging both analytic methods and user analysis, we can validate and even anticipate some of the findings. EHR navigation for a given task is a relatively finite space, and there are a small number of routes to task completion. The modeled pathways represent the most commonly observed rather than a complete set of possible trajectories. Also, we cannot conclude that one EHR is superior to another for the task of patient order management. There may be advantages to have a more extensive array of functions available at a given time. However, we believe that a more streamlined approach reduces navigational complexity and can alleviate some of the documentation burden issues and enhanced user experience.

Conclusions

The use of a navigational complexity framework helped identify interface design differences and how they can contribute to cognitive load and documentation burden. Expert-based and user-based analyses were applied to the POM task to understand better usability barriers at a more granular level and their effect on task performance and efficiency. The analyses completed in this paper identified interface design elements that differentially mediate task performance. By establishing system comparison tools to identify potential usability barriers in a system, issues can be identified to enhance the user experience, leading to a higher quality of care in workflow while informing optimization efforts.

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