NAVIGATION IN THE ELECTRONIC HEALTH RECORD: A REVIEW OF THE USABILITY AND SAFETY LITERATURE

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by

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ABSTRACT

Objective: Inefficient navigation in electronic health records has been shown to increase users' cognitive load, which may increase potential for errors, reduce efficiency, and increase fatigue. However, navigation has received insufficient recognition and attention in the electronic health record (EHR) literature as an independent construct and contributor to overall usability. Our aims in this literature review were to (1) assess the prevalence of navigation-related topics within the EHR usability and safety research literature, (2) categorize types of navigation actions within the EHR, (3) capture relationships between these navigation actions and usability principles, and (4) collect terms and concepts related to EHR navigation. Our goal was to improve access to navigation-related research in usability.

Materials and methods: We applied scoping literature review search methods with the assistance of a reference librarian to identify papers published since 1996 that reported evaluation of the usability or safety of an EHR user interface via user test, expert test, or inspection methods. The 4,336 references collected from MEDLINE, EMBASE, Engineering Village, and expert referrals were de-duplicated and screened for relevance, and navigation-related concepts were abstracted from the 21 papers eligible for review using a standard abstraction form.

Results: Of the 21 eligible papers, 20 (95%) mentioned navigation in results and discussion of usability evaluations. Navigation between pages of the EHR was the more frequently documented type of navigation (86%) compared to navigation within a single page (14%). Navigation actions (e.g., scrolling through a medication list) were frequently linked to specific usability heuristic violations, among which flexibility and efficiency of use, recognition rather than recall, and error prevention were most common.

Discussion: Discussion of navigation was prevalent in results across all types of evaluation methods among the studies reviewed. Navigating between multiple screens was frequently identified as a usability barrier. The lack of standard terminology created some challenges to identifying and comparing papers.

Conclusion: We observed that usability researchers are frequently capturing navigation-related issues even in studies that did not explicitly state navigation as a focus. Capturing and synthesizing the literature on navigation is challenging because of the lack of uniform vocabulary. Navigation is a potential target for normative recommendations for improved interaction design for safer systems. Future research in this domain, including development of normative recommendations for usability design and evaluation, will be facilitated by development of a standard terminology for describing EHR navigation.

BIOGRAPHICAL SKETCH

Lisette Roman received a Bachelor's of Arts in Psychology and French from Connecticut College in 2012. Her undergraduate training included an independent honors thesis examining the influence of environment on memory and a student research assistant role in neurobiology at Yale University in the laboratory of Amy Arnsten, MD. These undergraduate research experiences provide a formal theoretical foundation for her contribution to human-computer interaction research in the context of health information systems and medical errors. Ms. Roman has a formal training foundation in human subjects research as a research coordinator at Massachusetts General Hospital on multiple NIH-funded grants under the direction of Randy Gollub, MD, PhD, and Jian Kong, MD (equivalent), for whom she successfully recruited subjects and carefully carried out behavioral testing protocols. During 2013-2015 Ms. Roman was employed as a data analyst at Massachusetts General Hospital where she gained experience in quality and safety across inpatient and ambulatory psychiatry clinics, with an emphasis on the ambulatory electronic medical record (EMR). Her work included significant interaction with clinicians in the pursuit of quality improvement and patient safety issues related to their negotiation of the EMR. Specifically, she provided data analysis for quality improvement projects related to the ambulatory electronic medical record, including EMR note template improvements to facilitate enhanced substance use monitoring and the documentation of patient reported outcomes. Additionally, Ms. Roman supported administration of a web-based provider-oriented assessment of clinical competency in virtual patient assessment for more than 400 clinicians. Her experience with this web-based system and the ambulatory EMR provided knowledge pertinent to the medical widget-based information-sharing environment studied in the current project. Furthermore, her experience analyzing and implementing health IT solutions to fit the needs of a diversity of clinician roles, helped her appreciate the challenge and risks to patient safety inherent with inflexible health IT applications. As a result of these previous experiences, she was motivated to pursue a Masters of Science in health informatics in order to study how health IT can become nimbler to improve the quality of care a provider system delivers.

ACKNOWLEDGMENTS

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INTRODUCTION

Use of electronic health records in the United States has increased since 2009 due to federal investment in the adoption and use of these systems(1). Since the initial spike(2) in adoption, the clinician community has viewed electronic health records (EHRs) as an improvement to paper systems but has expressed frustration with the level of usability of available systems(3). Ellsworth and colleagues(4) described an increase in research of electronic health record (EHR) usability coinciding with the national spike in adoption: the number of usability studies increased from 10 between 2001 and 2005 to 63 between 2011 and 2015. This trend in research publications suggests that the prevalence of EHRs in patient care has brought usability issues of these systems to the fore.

The human-computer interaction literature defines usability as the degree of effectiveness, efficiency, and satisfaction with which users of a system can realize their intended task(5). The Institute of Medicine has recognized usable health information technology systems as one of the major challenges to providing safe and efficient care for patients(6). Research has highlighted a lack of adherence to user-centered design practices by commercial EHR vendors(7). Government and industry have formally recognized this challenge by publishing criteria for EHR certification(8) and standard guidelines for conduct of usability evaluations(9). These efforts collectively suggest an increasing shared view of the importance of research activity to identify desiderata for usable EHR systems.

Unfortunately, the EHR usability literature has suffered from poor reproducibility of evaluations due to variation in methodology and lack of standard reporting(4). Publications tend to be descriptive or qualitative in nature(10). We argue that another limitation of the usability literature is that an important construct, *navigation*, has not received sufficient recognition or attention. We define navigation as interaction with user interface presentation and controls that allows users to locate and access needed information(11) (Figure 1).

- Successful navigation means that users know where they are in the EHR, including in which patient's medical record they may be in at any given time.
- Users also ought to be able to engage navigation mechanisms to view relevant clinical data to meet their information needs.
- Similarly, we define *navigability* as the degree to which the presentation and controls of the EHR graphical user interface afford these actions.

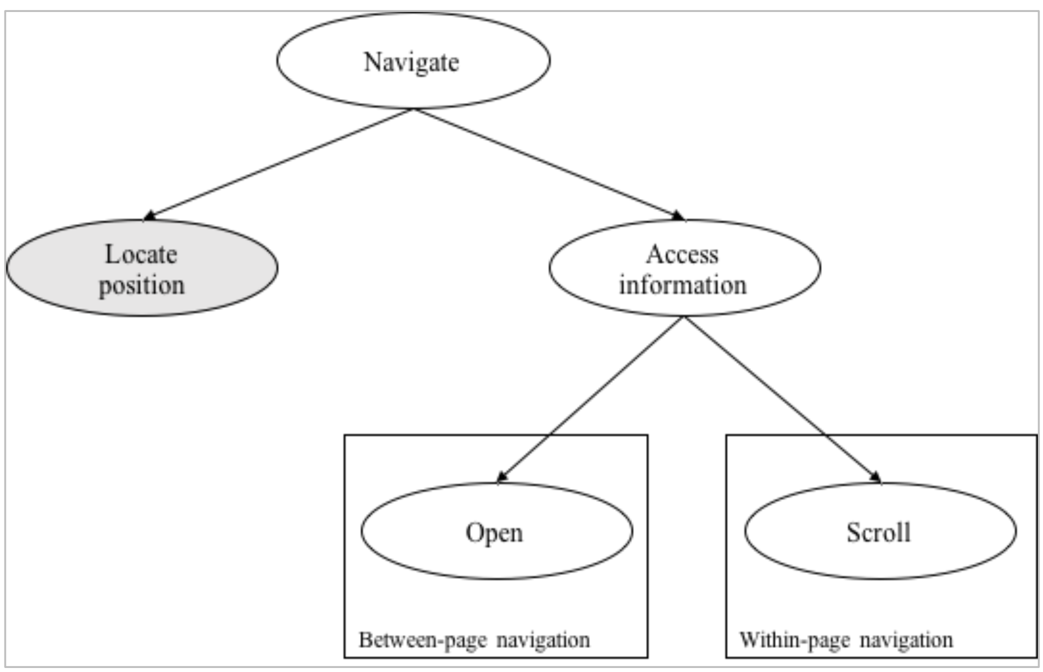

Figure 1. Classification of navigational actions in an electronic health record (gray shading represents concepts outside the scope of this paper)

Information in an individual patient record tends to be scattered across multiple screens and sections (12), forcing the clinician to navigate repeatedly through the digital space to create an adequate mental model of the patient's condition. This experience of viewing information 'through' a graphical user interface is analogous to attempting to view the contents of an entire room through a keyhole in a door to that room; this analogy is known as the keyhole effect by the artificial intelligence field(13). The clinician-user can view one screen at a time, increasing the challenge of piecing information together. The Institute of Medicine has termed this phenomenon 'display fragmentation'(6). The ability to juxtapose information in a single screen enables direct perception and comparison that can aid complex clinical decision-making, such as diagnostic reasoning. Clinicians attempt to view as much information as possible in order to avoid missing any relevant clinical information when under a time constraint(14). This switching pattern compensates for the poor EHR design but can exacerbate cognitive challenges. For example, computerized physician order entry system (CPOE) is a key functionality in EHRs as mandated by the federal Meaningful Use program(15). Up to 55% of resident physician-users of CPOE have reported difficulty identifying the correct patient and 72% have reported uncertainty identifying the right type or dosage of medication due to display fragmentation in the system(16). CPOE systems may require the clinician to view up to 20 distinct screens in order to see a single patient's entire list of medications(17).

Inefficient navigation in EHRs requires the user to store in working memory the information displayed on previous screens. When this cognitive load is too great, the user may forget the previously viewed information and need to view the same screen a second time(18). This navigation may reduce efficiency(18), increase cognitive load(19) by forcing the clinician to store information in working memory, and lead to medical errors(17, 20).

Despite this acknowledgment of the consequences of poor design for user interface navigation, it is unclear whether published EHR usability evaluations use a consistent terminology to describe navigation. Without a standard way to discuss the construct of navigation it is difficult to build on existing knowledge of the construct or compare navigation from one system to the next. This paper will address this gap by determining how navigation is discussed in the current EHR usability literature. Our goal in the current paper is to present findings from the scoping review.

METHODS

1. Overview of Methods

   We conducted two reviews for the current paper. (1) In a narrative review, we captured and synthesized concepts of navigation from computer science and the Web usability literature. We then applied these concepts to develop a standard data abstraction form for the scoping review. (2) In the scoping review, we identified usability evaluations of EHRs and abstracted concepts related to navigation from the eligible articles.

2. The Construct of Navigation in the World Wide Web

   2.1. Web navigation

   Web navigation has been defined in the field of computer science as 'actions performed by users to display a succession of Web pages to meet information needs'(21). The computer science literature has demonstrated the impact of specific design elements on various user experience outcomes, such as the clarity of a hyperlink title or button label on the user's opinion of the website's credibility(22). Additionally, computer scientists have proposed a conceptual framework of Web navigation (22), grounded in research in psychology, information science, and communication science. Collectively, these domains have demonstrated three key impacts of Web navigability on the user experience: ability to locate content of interest, ability to process content of interest, and the perception of the experience(23-25). Moreover, these efforts have enabled progress in quantifying the navigability of websites, an area of interest to online commercial retailers(26).

2.2. General Web Navigability

Because of the potential value of an easily navigable website for an online retailer, there has been interest in measuring and improving the navigability of websites(27-34) as reviewed by Vaucher and Sahraoui (11). The number of transactions reaped by an online retailer depends on how successfully a user is able to navigate the website, place items in a virtual shopping cart, and complete a purchase(35). As such, Web navigability has been defined as 'a measure of how easily a user can locate and access'(11) needed information. The degree of navigability impacts the user experience as an online customer interacts with the website user interface layout and controls in order to complete steps towards making a purchase.

Because a customer is likely to explore a website's homepage and subpages, a comprehensive model of Web navigability would capture the ease of a customer's navigation at both the system (website) and component (Web page) levels, as Vaucher and Sahraoui proposed in their multi-level evaluation model of Web navigability(11). In this model, navigability of a website depends on the mechanisms available to visitors at the website level (e.g., site map, menu, search mechanism) and at the individual Web page level (e.g., hypertext links, link to home page, back button). However, mechanisms available to visitors within the individual Web page (such as scrollbars), are not explicitly captured by this and similar models of Web navigation. Scrolling is implicit in Vaucher and Sahroui's construct of navigation in that they propose factoring in the size of a Web page in the navigability metric proposed by their model, such that larger pages require more scrolling to view the entire page's contents. However, the explicit user action of scrolling is not considered a navigation action itself. Instead, user actions within a page are characterized in aggregate as a lack of navigation action, in that users are not moving between pages; this lack of between-page navigation has been described as ‘staying in’(30).

3. Application of Navigation in the Web to Navigation in the Electronic Health Record

The underlying technology platform of an EHR is an internal or externally-hosted server. Internal server systems require the server, hardware, and software to be hosted at the user’s site, and externally-hosted servers (sometimes called web-based or cloud-based servers) require a computer with internet connection to access the server located off-site. Despite this distinction between underlying architecture, the user interface is comparable across EHRs, allowing for comparison of user navigation of the web and the EHR. When discussing EHR navigation, the analog to the webpage is the information screen, and the analog of page size is screen size or screen-element size. For example, a clinical note (an element of a larger EHR screen) may be extremely long and require the user to scroll to reach the bottom. In Web retail, a typical user goal might be to make an online purchase. By contrast, in the EHR, a typical user goal might be to complete the required documentation mandated by the reimbursement system.

On the Web, a user can often bypass navigation affordances by using a free text search engine to locate relevant information. By contrast, EHR search functions (when available at all) can search only certain components of the record, forcing users to rely upon the navigation affordances to open attached PDFs, lab reports, images, or other non-searchable information(36). Improved search functions for

EHRs may reduce the need for user interface-driven navigation. Until that improvement is realized, usability engineering focused on user interface design can address immediate challenges to more efficient user interface-driven navigation.

In light of this preliminary knowledge, we organized the identified concepts from the computer and information science literature on evaluation of Web navigation and from industry development guidelines on design for Web navigation. Informed by this knowledge base, we propose that a comprehensive construct of navigation for EHRs would capture navigation between and within pages of the EHR user interface.

1. Between-page: Navigation action to display new information by moving the user to a new page in the electronic health record (Figure 1).
2. Within-page: Navigation action to display new information by moving within the current page in the electronic health record (Figure 1).

First, by analyzing the usability evaluation publications according to these user actions, we aimed to describe the prevalence of discussion of navigation-related topics within the EHR usability and safety research literature. Second, we aimed to categorize types of navigation actions within the EHR and to capture relationships between these navigation actions and usability principles. Last, we collected terms and concepts related to EHR navigation.

4. Literature review

We conducted a literature review following the Preferred Reporting Items for Scoping reviews and Meta-Analysis statement(37). Our review was limited to articles published between 1996 and 2016 as in(38) to evaluate the prevalence of discussion of navigability in EHRs over time as EHR adoption increased in the United States and attention to usability issues increased. However, the literature was not limited to publications from the United States.

4.1. Data sources

A search of electronic databases was conducted in February-March 2016 using MEDLINE, EMBASE, and Engineering Village. This database search was supplemented with expert opinion contributions.

4.2. Search terms

The literature search terms included keywords in two categories: (1)electronic health records and (2)usability and safety evaluations. A medical school library research specialist was consulted to refine the electronic database queries. A combination of keywords was used to assure a comprehensive document search (Appendix Tables 1-3). The MeSH search term *Computerized Medical Records Systems* was used instead of the MeSH search term *Electronic Health Records* as advised by the library research specialist for the *Electronic Health Records* search term was implemented in 2010. Additionally, a gold standard patient safety search string(39) was used in the MEDLINE and EMBASE searches. The model with the highest precision of this validated patient safety search strategy was used (Appendix Tables 1-2). The Engineering Village literature search followed the Engineering Village Searching Best Practices for the database's Expert Search function.

4.3. Inclusion and exclusion criteria

Articles had to include evaluation of the usability or safety of an EHR user interface via test or inspection methods(40). As such, evaluations limited to subjective report of the user experience, such as user-completed questionnaires, were not included. We defined evaluation as an analysis of the EHR that described the user interface design, organization, or features. Furthermore, we required the scope of the EHR under evaluation to be the entire EHR (i.e., not a single page or module) to capture navigation within and across EHR pages. We defined EHRs as comprehensive medical information systems that contain data related to medical and treatment history for patients. This definition was chosen to be inclusive of international studies that do not follow, for example, the United States' Office of the National Coordinator of Health Information Technology definition of a certified electronic health record(8). As such, we opened our search to include 'medical record systems, computerized' in MEDLINE and EMBASE and 'medical information systems' in Engineering Village. We defined user interface as the graphical user interface. Only English-language studies were included in this review.

Articles that failed to meet the inclusion criteria included topics such as fragmentation of care in the healthcare system, position papers describing the need to address usability in EHRs, evaluations of EHR usability methodologies, or papers limited to a description of the design or implementation of an EHR without a usability evaluation of the designed/implemented system.

4.4. Article selection and analysis

Titles and abstracts from the final search strategy (N=4036) were reviewed for potential relevance by one of the authors (LR). Two authors (LR, YS) then reviewed the potentially relevant abstracts, and those that failed to meet inclusion criteria were excluded. The remaining articles were read in their entirety for eligibility. Results of the screening process are noted in the flow diagram in Figure 2. Two papers were added by expert opinion for a total of 21 papers. The full text of each of the remaining 21 articles was then read by one health IT safety and usability expert (YS) and one health informatics graduate student (LR).

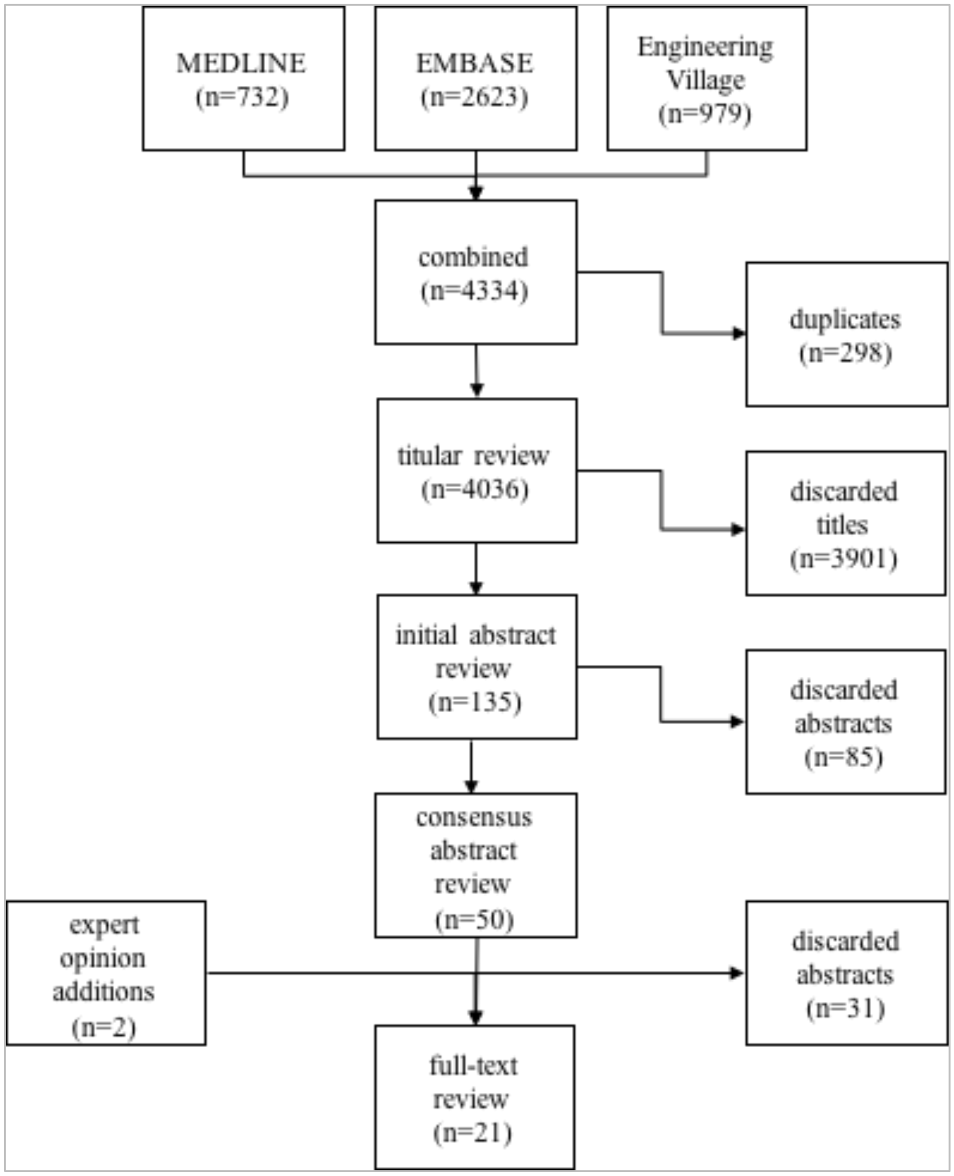

Figure 2. Article selection methodology

5. Qualitative analysis

5.1. Identification of excerpts

Articles were reviewed in detail to identify navigation in an EHR. Excerpts were limited to the Results and Discussion section of papers and identified at the level of sentence fragment, sentence, or paragraph. Excerpts were selected by one author (LR) and reviewed by a second author (YS). Disagreements were identified and final decision for inclusion or exclusion was reached by consensus review to produce a codebook. Excerpts were then independently coded by the two authors (LR, YS). The authors again met to reach consensus on the line-by-line coding of excerpts, including the relationships between concepts. Literature excerpts were annotated using ATLAS.ti™ software (ATLAS.ti 7, Scientific Software Development GmbH, Berlin, Germany).

5.2. Identification of concepts

We structured our process to identify concepts related to navigation and usability by coding for navigation actions and usability heuristics(41), respectively. Literature excerpts included both study author statements and study participant comments.

RESULTS

6. Literature review

A total of 4,334 references were retrieved from our initial search of electronic databases, specifically MEDLINE (n=732), EMBASE (n=2623), and Engineering Village (n=979). A request for expert suggestions yielded an additional 2 papers.

6.1. Titular review

Duplicate articles were removed (n = 298) by EndNote detection followed by manual comparison by author. All titles were reviewed independently by one author (LR). Titular review excluded 3,901 articles based on title. A title was excluded if it did not meet the inclusion criterion of usability evaluation of an EHR via primary data collection but instead was a review article, was limited to perceptions of usability, focused on patient-facing technology, aimed to describe EHR design or implementation, or was outside the scope of this review in some other way.

6.2. Initial abstract review

Abstracts of the 135 remaining articles were reviewed by a single author (LR). Articles were excluded at this stage of review if in the abstract there was no mention or allusion to the user interface of the EHR, if they described a methodology for usability evaluation without robust case examples, if they described the design and not evaluation of the interface, or if the usability evaluation was based on logfile analysis without description of user actions on screen. Of note, 22 were excluded due to the scope of the EHR under evaluation being limited to the medication or other type of physician-order entry modules. In total, 85 were excluded at this initial abstract review stage. Articles in question were retained for consensus abstract review.

6.3. Consensus abstract review

Abstracts of the 50 remaining articles were reviewed by two authors (LR, YS), and 31 articles were excluded (Table 1). One paper not discovered through the search strategy was added by expert opinion.

Table 1. Articles excluded from abstract review
UI: user interface; EHR: electronic health record

Reason for exclusion	N	Detailed explanation
Methodology paper	11	Description of methods with no robust case evaluation
Lack of UI description or analysis	5	Evaluations with no written or visual depiction of the UI or elements of the UI
Single EHR module	5	Articles that described usability evaluations of a single feature of EHR (e.g. Allergy module)
Abstract only	4	Articles with no full-text version available
Subject was user performance, not UI	2	Articles that compared the performance of two groups of EHR users
Not EHR	1	Evaluations of other clinical information systems
Single UI feature	1	Evaluations of a single feature of the UI (e.g. search function)
Limited to user perceptions	1	Evaluations of user perceptions without written or visual depiction of the UI or elements of the UI
Mobile version of EHR	1	Articles that described usability evaluations of mobile device versions of EHRs
Total	**31**	

6.4. Full-text review

The remaining 20 articles were reviewed by two reviewers, who independently populated a matrix developed for descriptive article analysis.

6.5. Analysis of articles

Articles were characterized by article and study characteristics and by evaluation methodology. Studies could be represented in multiple categories. For example, a 'Survey' methodology category exists due to the inclusion of inspection or test methodology studies that used more than one methodology during usability evaluation.

7. Characteristics of included articles

Publication dates ranged from 1997-2016. Fifteen (71%) of the studies were conducted in the United States. More studies evaluated homegrown systems (48%) than commercial systems (33%), and four (19%) of the studies provided inadequately detailed description of the system to determine whether it was a commercial product.

8. Characteristics of usability evaluations

Of the usability evaluations conducted, 9 (43%) used test methods, 7 (33%) used inspection methods, and 5 (24%) used both. Evaluation samples included participants with clinical training (nursing, medical, or dental) in 16 (76%) studies. Sample sizes ranged from 2-9 (24%), 10-19 (19%), and 20-68 (33%). Two of the studies inadequately detailed description of the sample size.

9. Characteristics of evaluation methodology

Evaluations included between 1 and 5 different evaluation methodologies (Table 2). The most common evaluation methodology was task analysis (57%) and heuristic evaluation (48%), followed by survey (24%), think aloud protocol (29%), and interview (29%). The least common methodologies included GOMS (goals, operators, methods, and selections) KLM (keystroke-level model) and Semiotic Inspection Method.

Table 2. Evaluation methodology characteristics
GOMS, goals, operators, methods, and selections; KLM, keystroke-level model
NB: Heuristic Walkthrough counted in both Heuristics and Cognitive Walkthrough

Characteristic	**Value**	**N**	**%**
Methodology	Task analysis	12	57
	Heuristic Evaluation	10	48
	Think aloud protocol	6	29
	Interview	6	29
	Survey	5	24
	Field observation	4	19
	Cognitive Walkthrough	2	10
	KLM	2	10
	GOMS	1	5
	Semiotic Inspection Method	1	5
Evaluation Type	Test methods	9	43
	Inspection methods	7	33
	Both	5	24
Evaluation Setting	Laboratory	15	71
	Naturalistic	5	24
	Both	1	5

10. Results of qualitative analysis

Navigation actions were mentioned in 20 of 21 articles reviewed (Table 3). The total number of mentions per article ranged from 1-19. Navigation between EHR pages was the most frequently mentioned type of navigation action (86%), followed by navigation within a single EHR page (14%). Navigation was mentioned in each usability evaluation methodology represented in the eligible article pool (e.g., task analysis, think aloud protocol), methodology type (inspection or test), and evaluation settings (laboratory or naturalistic).

Table 3. Frequency of navigation action by article

	Navigation action		
Article	**Between pages**	**Within pages**	**Total**
Ramsay 1997(42)	2	0	2
Scandurra 2006(43)	3	0	3
Edwards 2008(44)	11	0	11
Fairbanks 2008(45)	6	1	7
Thyvalikakath 2008(46)	3	0	3
Shachak 2009(47)	7	3	10
Zheng 2009(48)	6	6	12
Corrao 2010(49)	5	0	5
Saitwal 2010(50)	16	2	18
Senathirajah 2010(51)	10	1	11
Staggers 2010(52)	1	0	1
Ahmed 2011(53)	4	0	4
Kukec 2011(54)	6	1	7
Pereira 2012(55)	3	0	3
Hoyt 2013(56)	0	0	0
March 2013(57)	4	0	4
Rogers 2013(58)	6	2	8
Tancredi 2013(59)	6	2	8
Walji 2013(60)	2	1	3
Neri 2015(61)	15	0	15
Senathirajah 2016(18)	5	0	5
Total	**121**	**19**	**140**

Navigation between pages was described as problematic when it required users to navigate between multiple pages to complete a task, such as the need to navigate ‘across several windows’, ‘through two screens’, or ‘across a number of screen navigations'(53). Other terms used describe the need to navigate through a 'long, multi-screen admissions documentation entry process'(44), through a 'number of different data screens'(57), 'away' from the current screen(46, 55), 'between screens'(18), 'to the next tab'(60), by 'opening and closing charts'(47), 'from one screen to the other'(46), using 'sequential feature combinations' and switching between 'two features back and forth'(48), by 'additional navigation steps'(53), from 'screen to screen'(44), through 'dialogue flow'(50), by 'clicking through note, note, note'(51), and through '17 pages of stuff'(58). Navigation within pages was described as scrolling, 'scroll-down'(47), and 'scrollback'(58), and browsing within 'extremely large' lists(54).

Relationships between navigation actions and usability heuristics were then identified in the literature review to collect associations between a navigation action with its potential impact on usability. For example, scrolling (within-page navigation) could impact the degree to which the EHR affords Recognition rather than recall (usability). Unique mentions of these relationships were identified per article.

A total of 109 relationships between a navigation action and a usability heuristic violation were identified (Figure 3). An excerpt describing a single navigation action could appear in multiple usability heuristic violation categories. For example, a participant in one study observed that 'after selecting a consult timer, you must scroll down to click 'Save' and I would like it to go back to the 'Main' screen instead of back to the consult timer screen'(45). This observation describes navigation between pages, which violates both User control and freedom and Flexibility and efficiency. Therefore, navigation actions were captured in a one-to-many relationship when appropriate.

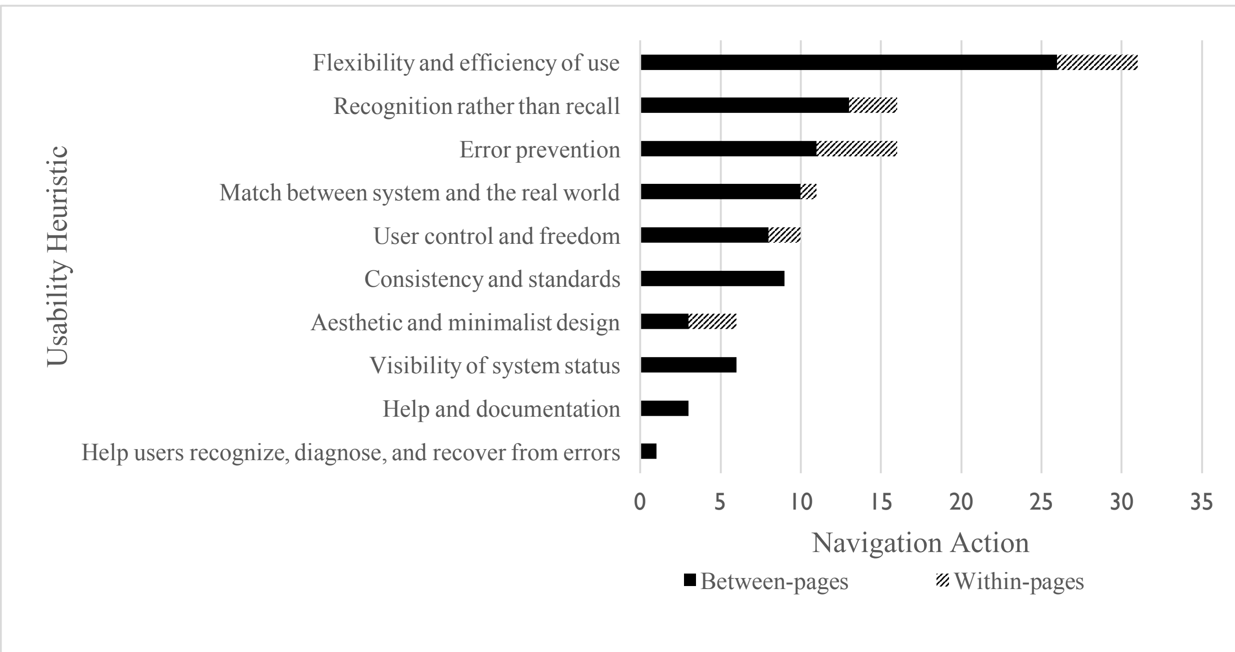

Figure 3. Frequency of literature excerpts linking navigation actions to violations of usability heuristics

Overall, the usability heuristic violations most frequently associated with any navigation were Flexibility and efficiency of use (31 unique instances), followed by

Recognition rather than recall (16 unique instances) and Error prevention (16 unique instances).

The usability heuristic violations most frequently associated with between-page navigation were Flexibility and efficiency of use (26 unique instances), followed by Recognition rather than recall (13 unique instances) and Error prevention (11 unique instances). Investigators and participants identified consequences of excessive between-page navigation, such as data entry errors (Table 4), including entering data into the incorrect patient chart(43).

The usability heuristic violations most frequently associated with within-page navigation were Flexibility and efficiency of use (5 unique instances) and Error prevention (5 unique instances). Scrolling was problematic when it impaired the user’s ability to locate information or data entry prompts (Table 4) and when it resulted in the user’s selection of an incorrect item or patient from a list(47).

Table 4. Literature excerpts demonstrating relationship between navigation action and usability heuristic violation

* Potential safety concerns of health IT components from the IOM 2011 report
**InspiredEHRs.org
*** https://www.healthit.gov/safer/guide/sg006

Excerpt	Navigation Action	Usability Heuristic	Safety Concern*	Potential Solution**
'You have to first select 'Patient', then 'All', then 'Forms', then which form and everything has to be done in a particular order. It would be easier if it was available as part of discharge instructions'(45). 'After selecting a consult timer, you must scroll down to click 'Save' and I would like it to go back to the 'Main' screen instead of back to the consult timer screen'(45) Similarly, 'Order' ↔ 'Medication' (32.77%) and 'Order' ↔ 'Laboratory Test' (18.6%) are two other frequently appearing feature combinations, in which 'Order' was more likely to be accessed before 'Medication' (72.5%) or 'Laboratory Test' (71.58%)[…]Note that we use the symbol ↔ to denote bidirectional feature transitions, for example a clinician may switch between 'Assessment and Plan' and 'Diagnosis' back and forth multiple times; whereas the symbol → denotes one-way feature transitions(48). 'Problem list should be visible or at least available on the screen as one is the	Between-page	Flexibility and efficiency of use	Increased ordering time; New opportunities for errors (e.g., fragmented displays preventing a coherent view of patients' condition or problems, inflexible ordering formats generating wrong orders); Disruptions in cognitive and/or clinical workflow	Provide a configurable interface that allows for juxtaposition of relevant information together on screen; Design compatible workflows, such as integration of context sensitive hyperlinks to frequently pages frequently accessed in succession

Table 4 (Continued)

Excerpt	Navigation Action	Usability Heuristic	Safety Concern*	Potential Solution**
discussion/plan'(49). In AHLTA, each separate encounter must be opened, reviewed for pertinent information, and closed before moving on to the next encounter document. This is an inefficient and time-consuming process, especially in the context of the time pressure of clinic schedules(52). '…for example you're not taking a social history of family history at every single visit but it'll show up in every single note...which takes up a lot of room and makes the note way longer than it has to be. The problem is that if you don't include it, if you want to see it, you have to go clicking through note, note, note and it takes forever'(51).	Between-page	Flexibility and efficiency of use	Increased ordering time; New opportunities for errors (e.g., fragmented displays preventing a coherent view of patients' condition or problems, inflexible ordering formats generating wrong orders); Disruptions in cognitive and/or clinical workflow	Provide a configurable interface that allows for juxtaposition of relevant information together on screen; Design compatible workflows, such as integration of context sensitive hyperlinks to frequently pages frequently accessed in succession
The majority of participants said they want to have vital signs taken during triage pre-populated into their progress note or have a way to easily import the vital signs from triage. The participants said that it can be difficult to view the triage note once they are in	Between-page	Recognition rather than recall	Increased note writing time; New opportunities for errors (e.g., fragmented displays preventing a coherent view of	Pre-populate templates (i.e., triage note) with data entered elsewhere (i.e., vital signs); Provide

Table 4 (Continued)

Excerpt	Navigation Action	Usability Heuristic	Safety Concern*	Potential Solution**
the middle of writing their note(61). Secondly, the complicated menu structure hindered workflow in that nurses expressed a burden in trying to locate where they were to document different aspects of the care(58). In order to accomplish this task users would need to navigate a tabbed user interface first to select a diagnosis, and then to select a treatment. However, once a diagnosis was selected, a user navigated to the next tab listing the treatments. This new tab failed to provide any indication of which diagnosis was actually selected in the previous screen. User testing showed the cognitive difficulty users had on retrieving memory the specific diagnosis, and many errors were made during this phase(60).			patients' condition with supporting data, inflexible documentation formats generating wrong information); Disruptions in cognitive and/or clinical workflow	graphical summaries of important patient information to minimize screen space and maximize comprehensibility; Configurable interface that allows for juxtaposition of relevant information together on screen; Smart data entry in which answering a particular question would automatically add/remove additional data entry fields in the screen
Several of these issues related to instances in which the system required	Between-page	Error prevention	Introduction of workaround	Pre-populate templates

Table 4 (Continued)

Excerpt	**Navigation Action**	**Usability Heuristic**	**Safety Concern***	**Potential Solution****
the users to reenter information. For example, when a set of new orders for a single patient is entered (which often occurs), the user had to enter much of the same information on each new order. However, on a case-by-case basis, the system could be configured to inherit information from previously completed forms. Utilizing this functionalist more would help alleviate the user's data entry workload and reduce opportunities for data entry errors(44). 'Need ability to refill multiple prescriptions at once(49).'			s (e.g., copy-and-paste); Increased ordering time; New opportunities for errors (e.g., incorrectly reentered information, copy-and-pasting extraneous, possibly outdated information); Disruptions in cognitive and/or clinical workflow	(i.e., orders) with data entered elsewhere (i.e., initial visit note); Smart data entry in which answering a particular question would automatically add/remove additional data entry fields in the screen
'A patient called to check something, so I opened his chart. When I returned to the visiting patient I forgot to close the new chart and continued writing in it instantly'(47).	Between-page	Error prevention	Increased relative risk of wrong patient errors	Prominent display of patient identifiers where important; Limit the number of patient records that can be open at once; Allow multiple patient records to

Table 4 (Continued)

Excerpt	**Navigation Action**	**Usability Heuristic**	**Safety Concern***	**Potential Solution****
				be open at once but make subsequent records Read Only or clearly demarcated ***
Very often the user is required to browse for a distinct item within extremely large drop-down lists and/or combo-boxes. This is regularly related to searching through various medical registries (primary healthcare service types, diagnosis descriptions, medication codes, etc.)(54). Sometimes it is possible to type a letter to see all options that start with this letter, i.e., to filter the content; sometimes the user must scroll an unsorted list and read all available options until the correct one is found(59). 'I can't always find the instruction templates I want and it takes time to keep trying to find them. To write a discharge instruction you have to guess what the system calls it. For example if someone has a bat bite, I'd first try 'bat bite,' but no results,	Within-page	Flexibility and efficiency of use	Introduction of workarounds (e.g., select first relevant item); Increased relative risk of diagnosis and medication errors; Increased ordering time; New opportunities for errors (e.g., fragmented display of list preventing a view of already-selected items; Disruptions in cognitive and/or clinical workflow	Simplify lists; Use preattentive attributes to highlight relevant options; Provide interactive tables to allow the user to sort and filter according to search needs; Provide flexibility regarding slight misspellings; Allow the user to begin to type desired item name and suggest options as the user types **

Table 4 (Continued)

Excerpt	**Navigation Action**	**Usability Heuristic**	**Safety Concern***	**Potential Solution****
then I'd try 'rabies,' again no results, and finally 'animal bite' works. It is time consuming, so usually I just free text my instructions'(45). *ADAD* (51.16%) and *DADA* (43.97%) are found to be the most commonly used sequential feature combinations, indicating that the CRS users often accessed 'Assessment and Plan' and 'Diagnosis' together and switched between these two features back and forth(48).				
'…a lot of times it will skip right over that safety piece [falls risk], so unless you know you have to document on it, it'll skip, it'll miss it…I have to usually go back and find it, like scroll back all the way up'(58).	Within-page	Error prevention	Increased documentation time, Increased relative risk of rework due to data entry omission; Inflexible documentation templates generate wrong information; Disruptions in cognitive and/or clinical workflow; Introduction of	Streamline data entry, such as by smart data entry in which answering a particular question would automatically add/remove additional data entry fields in the screen; Use minimalism to highlight

Table 4 (Continued)

Excerpt	**Navigation Action**	**Usability Heuristic**	**Safety Concern***	**Potential Solution****
			workarounds (e.g., document in other area of chart)	important areas for documentation
‘Name of tab is not reflective of its content(49)‘. In some cases, controls did not have affordances that made it readily apparent that they could be interacted with (e.g., were ‘clickable’). For example, some hyperlink text was not underlined and highlighted in a different color from the standard information (e.g., non-interactive text) and some clickable icons did not appear as buttons(44). By showing irrelevant and non-applicable menu options as clickable, the designers trick users into dead ends. For instance a menu option ‘display available health declarations’ is shown as clickable even when there aren’t any health declarations to display. When the user selects the option, an error message is displayed stating that there are no declarations to display(59).	Between-page	Visibility of System Status	Increased EHR interaction time; Inability to access needed information may impede clinical workflow	Use informative hyperlink text and titles; Communicate to user whether data exists in destination page

Investigators and participants identified ways to improve between- and within-page navigation. One common suggestion from investigators and participants was to bring relevant information together on one page by ‘pre-populating’(61) or designing pages to ‘inherit’(44) information from other pages, which may reduce errors related to data reentry. Participants expressed the desire to minimize within- and between-page navigation by use of ‘hyperlink shortcuts or ‘take me to’ buttons’ (44), dashboards, such as ‘a single screen summarizing key clinical data’ and ‘a multi-panel view […] allowing concomitant views’(57), and by integrating ‘relevant information and data using less windows and screens(46) in order to have information available during other tasks(41), to ‘do [things] side by side’(54). Likewise, participants expressed the desire to minimize the inefficiencies of between-page navigation by ‘speed[ing] up the dialogue flow’(50).

DISCUSSION

We completed four aims in this study. First, we assessed the prevalence of navigation-related topics within the EHR usability and safety research literature. All but one article (95%) reviewed in this study reported navigation actions in their EHR usability evaluation. This finding suggests that usability researchers are already capturing navigation-related issues, albeit not as a primary aim of usability evaluation. Furthermore, navigation was mentioned regardless of usability evaluation methodology despite the diverse range of inspection and test methodologies included in eligible articles. These findings collectively suggest that navigation is a cross-cutting construct relevant to usability evaluations.

Second, we categorized types of navigation actions within the EHR and captured relationships between these navigation actions and usability principles. Based on narrative review of the general Web navigation literature, we identified a need for the construct of EHR navigation to include within-page user actions in addition to between-page user actions. The scoping literature review demonstrated that navigation between and within pages in the EHR was prevalent in the literature and that both levels of navigation linked to usability heuristic violations, some with implications for patient safety. Although between-page navigation was more prevalent, both between- and within-page navigation were linked to Error prevention.

Multiple papers identified usability challenges related to navigating between and within pages in the EHR (Table 4). Some recommendations to address these challenges were identified in the literature, and we have linked usability challenges, safety effects, and potential solutions, including mechanisms for smart data entry and grouping together relevant information on a single page. Demonstrated elsewhere, an additional design method to reduce navigation is the use of in-line, or non-interruptive, clinical decision support in lieu of additional dialog boxes during a user's workflow. The in-line method presents users with information located on a screen normally invisible to them at the time. This type of non-interruptive alert can be safely incorporated into a clinician-users workflow to help combat alert fatigue(62) and decrease unnecessary laboratory ordering(63). The common strategy to improve EHR navigation suggested by this literature review was to reduce the number of actions required by users to display needed information. This strategy was often proposed by users in the desire to juxtapose clinically relevant information together on-screen to facilitate cognition. Such juxtaposition of clinical information elements in the digital space of the EHR is a predictable form of intelligent use of space as described in the literature on work practices and cognitive science(64). Juxtaposition of information via flexible systems would address the problems inherent in the keyhole effect and resulting display fragmentation, which are sources of potential error, as described by the Institute of Medicine(6). Display fragmentation presents particular dangers in EHRs because of the high cognitive demands of clinical reasoning, often in stressed conditions. Thus there is great need for information systems that do not place unnecessary load on working memory, freeing the user's cognitive resources for higher reasoning. Therefore, improving EHR navigation may result in multiple benefits to users, such as cognitive support for complex clinical reasoning, in addition to greater efficiency and advantages for patient safety.

By completing this literature review, we collected terms and concepts related to EHR navigation. The variance of terminology (e.g., navigation action verbs, user interface components) used to describe concepts related to navigation created some challenges to identifying and comparing papers. This result demonstrated a barrier to a clearer description of navigation in EHRs.

The collection of specific instances of navigation problems may also serve as a starting point for explanation of the problems to interaction designers in our search for comprehensive design solutions.

Limitations of this study include the small number (n=21) of articles determined to be eligible for review. However, this small yield was somewhat expected based on the recent scoping review by Ellsworth and colleagues(4) that demonstrated low reproducibility and a large amount of qualitative findings in EHR evaluation research. This fact, in addition to our strict inclusion criteria (for example, the requirement for evaluations to use test or inspection methods), reduced the corpus of eligible literature for consideration. Notably, our decision to include only evaluations of entire EHRs meant excluding papers on computerized provider-order entry modules when the evaluation was limited to the single module, meant excluding a robust portion of the EHR-related usability literature. This limitation was accepted as a compromise to ensure we would capture substantial between-screen navigation, such as that which frequently occurs with clinician-users needs to access multiple modules for a single EHR-based clinical task. It is likely that inclusion of papers limited to computerized provider-order entry modules would have increased the prevalence of within-page navigation actions because scrolling has been linked to electronic prescribing errors, whether scrolling through large EHR pages(65) or individual drop-down lists(66).

CONCLUSION

Improving our understanding of navigation and what constitutes ideal pathways in clinical tasks that require use of the EHR is one aspect of the larger goal to improve EHR usability engineering. We observed that that navigation was frequently mentioned in EHR usability evaluations albeit seldom independently the primary aim. This observation suggests that navigation is a potential target for normative recommendations for EHR usability design and evaluation. To this end, future research should address the lack of standard terminology for describing EHR navigation. Ultimately, the ability to describe navigability across systems may be of national interest in improving interaction design for safety.

APPENDIX

Appendix Table 1. Electronic literature search terms for EMBASE[1]

EMBASE (OVID) 1974 to 2016 Week 06

1	Medical Records Systems, Computerized/	33513
2	limit 1 to yr='1996 -Current'	33488
3	((interaction or interface) adj2 design).tw.	1032
4	usability.tw.	7949
5	(Exp Safety/ OR Err$. ti,ab.) AND (patient$.ti,ab.) AND (Exp Health Care Organization/ OR Exp Health Care/ OR Medic$.ti,ab. OR Exp Health Care System/ OR Hospital$.ti,ab.)	154972
6	3 or 4 or 5	163403
7	**1 and 2 and 6**	**2623**

Appendix Table 2. Electronic literature search terms for MEDLINE

MEDLINE (OVID) In-process & Other Non-Indexed Citations and Ovid MEDLINE(R) 1946 to Present

1	Medical Records Systems, Computerized/	28736
2	limit 1 to yr='1996 -Current'	26220
3	((interaction or interface) adj2 design).tw.	803
4	usability.tw.	6291
5	*Medical Errors/	9401
6	3 or 4 or 5	16345
7	**1 and 2 and 6**	**732**

Appendix Table 3. Electronic literature search terms for ENGINEERING VILLAGE

1	(medical information systems) WN CV	
2	(user interfaces) WN CV	
3	(user centred design) WN CV	
4	(human computer interaction) WN CV	
5	(safety)	
6	(safety-critical software) WN CV	
7	(English) WN LA	
8	2 or 3 or 4 or 5 or 6	
9	**1 and 7 and 8**	

REFERENCES

1 Charles D, Gabriel M, Furukawa M. Adoption of electronic health record systems among US non-federal acute care hospitals: 2008-2013. Washington, D.C.; 2014. https://www.healthit.gov/sites/default/files/data-brief/2014HospitalAdoptionDataBrief.pdf (accessed May 2016).
2 Jha CMD, Dustin C, Michael FF, et al. Adoption of electronic health records grows rapidly, but fewer than half of US hospitals had at least a basic system In 2012. *Health Aff (Millwood)*. 2013 2013-08-01;**360**(16):10-1377.
3 Friedberg M, Chen P, Van Busum K, et al. Factors affecting physician professional satisfaction and their implications for patient care, health systems, and health policy. 2013.
4 Ellsworth MA, Dziadzko M, O'Horo JC, Farrell AM, Zhang J, Herasevich V. An appraisal of published usability evaluations of electronic health records via systematic review. *Journal of the American Medical Informatics Association : JAMIA*. 2016:ocw046.
5 Bevan N. International standards for HCI and usability. *Int J Hum-Comput St*. 2001;**55**(4):533–52.
6 Institute of Medicine. Health IT and Patient Safety: Building Safer Systems for Better Care. Washington, DC:The National Academies Press;2011.
7 Ratwani R, Fairbanks R, Hettinger A, Benda N. Electronic health record usability: analysis of the user-centered design processes of eleven electronic health record vendors. *Journal of the American Medical Informatics Association : JAMIA*. 2015;**22**(6):1179-82.
8 McFarland DJ. The advantages of the surface laplacian in brain–computer interface research. *International Journal of Psychophysiology*. 2015;**97**(3):271-6.
9 Lowry S, Quinn M, Ramaiah M, et al. Technical evaluation, testing, and validation of the usability of electronic health records. National Institute of Standards and Technology. 2012:65-87.
10 Zahabi M, Kaber D, Swangnetr M. Usability and safety in electronic medical records interface design. *Hum Factors*. 2015;**57**(5):805-34.
11 Vaucher S, Sahraoui H. Multi-level evaluation of web site navigability. Web Systems Evolution (WSE), 2010 12th IEEE International Symposium; 2010 17-18 Sept. 2010; Timişoara, Romania: IEEE; 2010. p. 93-100.
12 Rule A, Rick S, Chiu M, et al. Validating free-text order entry for a note-centric EHR. AMIA Annu Symp Proc; 2015; 2015. p. 1103-10.
13 Woods DD. Paradigms for Intelligent Decision Support. In: Heidelberg SB, editor. Intelligent Decision Support in Process Environments: Springer Berlin Heidelberg; 1986. p. 153-73.
14 Gold JA ea. Feasibility of utilizing a commercial eye tracker to assess electronic health record use during patient simulation. *Health Informatics J*. 2015.
15 Computerized Physician Order Entry (CPOE) for Medication, Laboratory and Radiology Orders | Providers & Professionals | HealthIT.gov. 2015 [cited; Available

from: https://www.healthit.gov/providers-professionals/achieve-meaningful-use/core-measures-2/computerized-physician-order-entry-cpoe-medication-laboratory-and-radiology
16 Koppel R, Metlay JP, Cohen A, et al. Role of Computerized Physician Order Entry Systems in Facilitating Medication Errors. *JAMA*. 2005;**293**(10):1197-203.
17 Koppel R, Metlay J, Cohen A, et al. Role of Computerized Physician Order Entry Systems in Facilitating Medication Errors. *JAMA*. 2004;**293**(10):1197-203.
18 Senathirajah Y, Kaufman DR, Bakken SR. User-composable electronic health record improves efficiency of clinician data viewing for patient case appraisal: A mixed-methods study. *eGEMs*. 2016;**4**(1):7.
19 Milord JT, Perry RR. A Methodological Study of Overload. *Journal of General Psychology*. 1977;**97**:131-7.
20 Ash J, Gorman P, Seshadri V, Hersh W. Computerized physician order entry in U.S. hospitals: Results of a 2002 survey. *Journal of the American Medical Informatics Association : JAMIA*. 2004;**11**(2):95-9.
21 David KF, farkas@u.washington.edu, Human Centered D, Engineering, Farkas JB. Guidelines For Designing Web Navigation. *Technical Communication*. 2016;**47**(3).
22 Wojdynski BW, Kalyanaraman S. The three dimensions of website navigability: Explication and effects. *J Am Soc Inf Sci Tec*. 2016;**67**(2):454-64.
23 Jacek Gwizdka IS. Implicit Measures of Lostness and Success in Web Navigation. *Interacting with Computers*. 2007;**19**(3).
24 Marchionini, Gary. Information Seeking in Electronic Environment. 1996;**9**.
25 S. Shyam Sundar SKJB. Explicating Web Site Interactivity. *Communication Research - COMMUN RES*. 2003;**30**(1).
26 Lee Y, Kozar K. Investigating the effect of website quality on e-business success: An analytic hierarchy process (AHP) approach. 2006 December 2006;**42**(3):1383–401.
27 Luis O, Unlpam, Guillermo L, Lifia ISaU, Gustavo R, Lifia ISaU. Specifying Quality Characteristics and Attributes for Websites. 2001:266-78.
28 Greenwood YZ, Hong Z, Sue. Website Complexity Metrics for Measuring Navigability. IEEE Computer Society; 2004.
29 Newman MW, Landay JA. Sitemaps, storyboards, and specifications: a sketch of Web site design practice. Proceedings of the 3rd conference on Designing interactive systems: processes, practices, methods, and techniques; 2000 08/01/2000: ACM; 2000. p. 263-74.
30 Winoto YZ, Hareton L, Pinata. MNav: A Markov Model-Based Web Site Navigability Measure. 2007 2007-09-10.
31 Calero CCC, Santiago M, Marcela G, Geert P, Coral. Towards improving the navigability of Web applications: a model-driven approach. *European Journal of Information Systems*. 2007 2007-08-01:420-47.
32 Schubert P. Extended Web Assessment Method (EWAM): Evaluation of Electronic Commerce Applications from the Customer's Viewpoint on JSTOR. *International Journal of Electronic Commerce*. 2003;**7**(2):51-80.
33 Andreou SM, A.S. WAQE: a Web Application Quality Evaluation model. 2006 2006-12-04.

34 Caro A, Calero C, de Salamanca JE, Piattini M. Refinement of a Tool to Assess the Data Quality in Web Portals. Proceedings of the Seventh International Conference on Quality Software; 2007 10/11/2007: IEEE Computer Society; 2007. p. 238-43.
35 Nielsen J, Loranger H. Prioritizing Web Usability: Pearson Education; 2006.
36 Natarajan K. Analysis of Search on Clinical Narrative within the EHR: Columbia University; 2012.
37 Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS medicine*. 2009 Jul 21;**6**(7):e1000097.
38 West VL, Borland D, Hammond WE. Innovative information visualization of electronic health record data: a systematic review. 2015 2015-03-01.
39 Tanon AA, Champagne F, Contandriopoulos AP, Pomey MP, Vadeboncoeur A, Nguyen H. Patient safety and systematic reviews: finding papers indexed in MEDLINE, EMBASE and CINAHL. *Quality & safety in health care*. 2010 Oct;**19**(5):452-61.
40 Kushniruk A, Patel V. Cognitive and usability engineering methods for the evaluation of clinical information systems. 2004 February 2004;**37**(1):56–76.
41 Nielsen J. Enhancing the explanatory power of usability heuristics. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems; 1994 04/24/1994: ACM; 1994. p. 152-8.
42 Ramsay J, Popp HJ, Thull B, Rau G. The evaluation of an information system for intensive care. *Behaviour and Information Technology*. 1997 01/;**16**(1):17-24.
43 Scandurra I, Hagglund M, Mostrom D, Koch S. Heuristic evaluation extended by user analysis: A fast and efficient method to identify potential usability problems in health information systems. *Journal on Information Technology in Healthcare*. 2006 October;**4**(5):317-25.
44 Edwards PJ, Moloney KP, Jacko JA, Sainfort F. Evaluating usability of a commercial electronic health record: a case study. *International Journal of Human-Computer Studies*. 2008 10/;**66**(10):718-28.
45 Fairbanks RJ, Guarrera TK, Karn KS, Caplan SH, Shah MN, Wears RL. Interface design characteristics of a popular emergency department information system. Human Factors and Ergonomics Society 52nd Annual Meeting, 22-26 Sept 2008; 2008; Santa Monica, CA, USA: Human Factors and Ergonomics Society; 2008. p. 778-82.
46 Thyvalikakath TP, Monaco V, Thambuganipalle HB, Schleyer T. A usability evaluation of four commercial dental computer-based patient record systems. *Journal of the American Dental Association*. 2008;**139**(12):1632-42.
47 Shachak A, Hadas-Dayagi M, Ziv A, Reis S. Primary care physicians' use of an electronic medical record system: A cognitive task analysis. *Journal of General Internal Medicine*. 2009 March;**24**(3):341-8.
48 Zheng K, Padman R, Johnson MP, Diamond HS. An Interface-driven Analysis of User Interactions with an Electronic Health Records System. *Journal of the American Medical Informatics Association*. 2009 March 2009/April;**16**(2):228-37.
49 Corrao NJ, Robinson AG, Swiernik MA, Naeim A. Importance of testing for usability when selecting and implementing an electronic health or medical record system. *Journal of Oncology Practice*. 2010 May;**6**(3):120-4.

50 Saitwal H, Feng X, Walji M, Patel V, Zhang J. Assessing performance of an Electronic Health Record (EHR) using Cognitive Task Analysis. *International Journal of Medical Informatics*. 2010 July;**79**(7):501-6.
51 Senathirajah Y, Kaufman D, Bakken S. Cognitive Analysis of a Highly Configurable Web 2.0 EHR Interface. *AMIA Annual Symposium proceedings / AMIA Symposium AMIA Symposium*. 2010;**2010**.
52 Staggers N, Jennings BM, Lasome CE. A usability assessment of AHLTA in ambulatory clinics at a military medical center. *Military Medicine*. 2010;**175**(7):518-24.
53 Ahmed A, Chandra S, Herasevich V, Gajic O, Pickering BW. The effect of two different electronic health record user interfaces on intensive care provider task load, errors of cognition, and performance. *Critical Care Medicine*. 2011 July;**39**(7):1626-34.
54 Kukec M, Ljubic S, Glavinic V. Need for Usability and Wish for Mobility: Case Study of Client End Applications for Primary Healthcare Providers in Croatia. Information Quality in e-Health 7th Conference of the Workgroup Human-Computer Interaction and Usability Engineering of the Austrian Computer Society, USAB 2011, 25-26 Nov 2011; 2011; Berlin, Germany: Springer Verlag; 2011. p. 171-90.
55 Pereira R, Duarte J, Salazar M, et al. Usability evaluation of Electronic Health Record. 2012 IEEE EMBS Conference on Biomedical Engineering and Sciences (IECBES 2012), 17-19 Dec 2012; 2012; Piscataway, NJ, USA: IEEE; 2012. p. 359-64.
56 Hoyt R, Adler K, Ziesemer B, Palombo G. Evaluating the usability of a free electronic health record for training. *Perspectives in health information management / AHIMA, American Health Information Management Association*. 2013;**10**:1b.
57 March CA, Steiger D, Scholl G, Mohan V, Hersh WR, Gold JA. Use of simulation to assess electronic health record safety in the intensive care unit: A pilot study. *BMJ Open*. 2013;**3 (4) (no pagination)**(e002549).
58 Rogers ML, Sockolow PS, Bowles KH, Hand KE, George J. Use of a human factors approach to uncover informatics needs of nurses in documentation of care. *International Journal of Medical Informatics*. 2013 November;**82**(11):1068-74.
59 Tancredi W, Torgersson O. An example of an application of the semiotic inspection method in the domain of computerized patient record system. *Studies in health technology and informatics*. 2013;**192**:471-5.
60 Walji MF, Kalenderian E, Tran D, et al. Detection and characterization of usability problems in structured data entry interfaces in dentistry. *International Journal of Medical Informatics*. 2013 February;**82**(2):128-38.
61 Neri PM, Redden L, Poole S, et al. Emergency medicine resident physicians' perceptions of electronic documentation and workflow: a mixed methods study. *Applied Clinical Informatics*. 2015;**6**(1):27-41.
62 Bates SP, Heleen van der S, Alisha DT, et al. Drug—drug interactions that should be non-interruptive in order to reduce alert fatigue in electronic health records. 2013 2013-05-01.
63 May TA, Clancy M, Critchfield J, et al. Reducing unnecessary inpatient laboratory testing in a teaching hospital. *American journal of clinical pathology*. 2006 Aug;**126**(2):200-6.

64 Kirsh D. The intelligent use of space. *Artificial Intelligence*. 1995;**73**(1-2):31-68.
65 Hawsey, Anthony GP, Bradley ND, et al. Applying human factors principles to alert design increases efficiency and reduces prescribing errors in a scenario-based simulation. 2014 2014-10-01.
66 Coiera FM, Mei-Sing O, William R, Enrico. Using FDA reports to inform a classification for health information technology safety problems. 2012 2012-01-01.