



## Electronic health record usability and workload changes over time for provider and nursing staff following transition to new EHR

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### ABSTRACT

The ubiquity of EHRs in healthcare means that small EHR inefficiencies can have a major impact on clinician workload. We conducted a sequential explanatory mixed methods study to: 1) identify EHR-associated workload and usability effects for clinicians following an EHR change over time, 2) determine workload and usability differences for providers (MD and Advance Practice Nurses) versus nurses (RNs and MAs), 3) determine if usability predicts workload, 4) identify potential sources of EHR design flaws. Workload (NASA-Task Load Index) and usability (System Usability Scale) measures were administered pre, 6–8 month and 30–32 months post-implementation. We found significant increase in perceived workload post-implementation that persisted for 2.5 years ( $p < .001$ ). The workload increase was associated with usability ratings, which in turn may relate to EHR interface design violations identified by a heuristic evaluation. Our findings suggest further innovation and attention to interface design flaws are needed to improve EHR usability and reduce clinician workload.

### 1. Introduction

The use of computers in healthcare began over five decades ago (Bernier et al., 2005; Hanauer et al., 2016; National Institutes of Health, 2006), although adoption of Electronic Health Records (EHRs) was not widespread until passage of the HITECH (Health Information Technology for Economic and Clinical Health) Act in 2010. HITECH required specific features (e.g. electronic medication prescribing and decision support) referred to as Meaningful Use (MU) criteria, with the goal of improving the safety, quality and efficiency of care. This program has since evolved into the Merit-Based Incentive Program, but HITECH's strong financial incentives (The Office for the National Coordinator of Health Information Technology, 2016) and the subsequent multibillion dollar federal investment has dramatically transformed how computers are used by clinicians during routine clinical workflow (Benda et al., 2016; Sinsky et al., 2016; Tai-Seale et al., 2017).

Although these MU electronic health records (EHRs) have demonstrated important benefits on some safety and quality outcomes (Ancker

et al., 2015; Hyman et al., 2017; Kern et al., 2013; Nuckols et al., 2014), they also sometimes introduce new risks and unintended negative consequences (Carayon et al., 2019; Gawande, 2018; Gephart et al., 2015; Howe et al., 2018; Kim et al., 2017; Landman et al., 2013; Meeks et al., 2014; Schulte and Fry, 2019; Sheehy et al., 2014; Wright et al., 2016; Zayas-Caban and White, 2020). One area of concern is the increased complexity of cognitive work associated with ordering care, finding patient information, and documenting care; all tasks now mediated by EHR use (Ariza et al., 2015; E. Gardner, 2015; McCluskey, 2016; Willard, 2020). Physicians, for example, now spend nearly half of their day using EHRs (Mamykina et al., 2016; Sinsky et al., 2016). This includes over one-third of time in the exam room entering and looking for data in the EHR while delivering care (Sinsky et al., 2016) that was formerly done in a paper-based system after the patient visit. Clinicians have had to adapt to using systems these with complex interfaces that can increase the number of tasks (Arndt et al., 2017; Benda et al., 2016) and decrease the efficiency of accomplishing these tasks (Ariza et al., 2015), essentially leaving them at the mercy of EHR design flaws.

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The ubiquity of the EHR in mediating clinical tasks means that even small inefficiencies or design flaws in EHRs can have a major impact on clinical workload. For example, documenting care, once as simple as writing or typing a few lines of free text, now requires multiple computer clicks, dropdown menus, check-boxes and multiple steps of choosing from lists of structured terminologies and adding information to specific fields (Benda et al., 2016; Gardner et al., 2019; Willyard, 2020). Not surprisingly, EHR, usability and workload were a concern for clinicians in the early years following the HITECH Act. However, clinicians' concerns about EHRs do not appear to be lessening over time even as they have gained more experience with these new systems (Hanauer et al., 2016; Hanauer et al., 2016; Shanafelt et al., 2016; Sinsky et al., 2016; Beasley et al., 2020). More recently physician burnout has been associated with EHR use (Gardner et al., 2019; Melnick et al., 2019).

These persistent concerns are surprising because there are reasons to believe that initial increased workload after EHR implementation should diminish over time. First, clinicians should become more proficient in doing the work as they learn new EHR-based tasks. In general, repeated performance of steps involved in sequential tasks (e.g., e-prescribing) should demand less attention (Ackerman, 1988). Second, clinicians may learn adaptive strategies (e.g., workarounds and short-cuts) to cope with usability challenges (Blijleven et al., 2017; Menon et al., 2016). On the other hand, it is possible that elevated workload associated with the introduction of EHRs may not return to previous levels because of persistent usability problems as well as the additional EHR-mediated tasks required by MU regulations.

Despite its importance to health care, clinicians' adaptation over time to MU-EHR implementation has not been extensively investigated. The few studies that have examined clinicians' adaptation to MU-EHRs study over different time periods have produced mixed results. Colligan and colleagues, whose study spanned 4 months, found significantly higher cognitive workload for registered nurses (RNs) after the first and 5th shifts following new EHR implementation for nurses ( $N = 74$ ,  $p < 0.001$ , with a return to pre-implementation ratings between 3 weeks and 4 months' time (Colligan et al., 2015). Zadvinskis, Smith and Yen (2018) assessed nurses' perceptions and concerns at 3, 9 and 18 months following EHR implementation and found nurses were the most dissatisfied at 9 months (Zadvinskis et al., 2018). Similarly, nurses' usability problems, frustration and high mental demand persisted after one year of extensive EHR use (Kjeldskov et al., 2010). For physicians (MDs), both Hanauer et al. (2016) and Krousel-Wood et al. (2018) found decreased "satisfaction" with multiple aspects of EHR use including usability up to two years after EHR implementation (Hanauer et al., 2016; Krousel-Wood et al., 2018). Walker et al. (2020) found that the time devoted to nurses devoted to documentation increased one and a half years following EHR system change. In contrast, Ryan and colleagues found MDs' perceptions of "ease of use" were greater in the group that had been using an EHR two years or longer when compared with the MDs that had been using EHRs 6–12 months post implementation (Ryan et al., 2014). Abramson et al. (2012) found that physicians did not perceive improved medication safety, but in their subsequent study found lower error rates up to 2 years after EHR transition. In sum, the longest time period we identified was 2 years following implementation of a new EHR system and the majority of studies in this area used measures of satisfaction, frustrations and concerns (Saleem and Herout, 2018).

We identified no studies that included both RNs and providers (includes MDs and Advance Practice Nurses). While it is understandable that some technologies such as EHRs are designed to be used primarily by one profession (e.g., bar code medication administration for nurses and medication ordering for providers), both professions use EHRs extensively throughout their workday to plan, provide and document clinical care. In addition, we were unable to identify any studies longer than 2 years post EHR implementation. Thus, there is a gap in knowledge about clinicians' adaptation to new EHR systems over time and whether RNs' and providers' adaptation patterns differ.

## 1.1. Study aims

We addressed the following aims:

- 1) Identify effects of MU-EHR adoption on clinicians' perceived workload and usability over time. We predicted workload would increase and usability decrease immediately after adoption of the EHR system that must be used in the context of delivering care to patients. We also investigated whether these effects persisted over time.
- 2) Determine whether EHR workload and usability differed by clinician role. We predicted that changes in workload and usability would be greater for providers, who must cope with a much greater increase in EHR-based work.
- 3) Determine whether clinician cognitive workload is associated with EHR usability, as predicted by our framework.
- 4) As a secondary aim, we explored potential EHR design flaws that may underlie inadequate usability by conducting a heuristic analysis.

## 1.2. Conceptual model

We propose a conceptual model that focuses broadly on Health Information Technology (HIT) design, clinician, and system factors in relation to patient outcomes and safety (Fig. 1). The model is based on the Technology Acceptance Model (TAM) (Venkatesh and Davis, 2000) and the Systems Engineering Initiative for Patient Safety (SEIPS) model (Carayon et al., 2020). From TAM, we include perceived usability but omit "perceived usefulness", "intention to use", and "actual use" because use of the EHR is mandatory in our target setting. From the SEIPS model, we focus on the broader organizational context within which EHR-based work is embedded and how these factors influence the work processes and patient outcomes. The model considers cognitive workload as resulting from usability, HIT design and clinician factors. Although measures of every concept in this model are not included in the current study, the model can guide future research that examines more broadly the impact of HIT design on workload and identifies specific problems that if corrected can improve EHR usability, clinician workload and indirectly patient outcomes.

## 2. Method

We conducted a mixed method approach that included a quasi-experimental between-subjects pre-post study with 3 time points: 2 weeks prior to new EHR implementation, as well as 6–8 and 30–32 months' post-EHR implementation. We chose the 6-month period because of evidence the clinics had returned to routine operations following the EHR change (e.g. reduction in calls to help desk, return to normal staffing levels). We chose the 30–32-month period to investigate whether prolonged experience with the new EHR reduced any shorter-term effects of adoption on clinician workload and usability.

We then conducted a retrospective Heuristic Evaluation. In Heuristic Evaluation, expert evaluators analyze interfaces and processes to identify areas of confusion, navigation problems, etc. using basic usability principles that can be corrected in redesign (Lowry, Quinn, & Ramaiah; Nielsen, 1993; Zhang et al., 2003). Although Heuristic Evaluation studies are typically conducted during early stages of IT design (Nielsen, 1993), our retrospective Heuristic Evaluation was useful for uncovering interface issues that may underlie clinicians' perceptions of EHR usability and workload (Zhang et al., 2003).

### 2.1. Setting and context

Data were collected in two ambulatory urgent care centers within one healthcare system using the same EHR system in a small Midwestern metropolitan area. These centers provide same day walk-in appointments for minor illnesses (e.g. colds, migraine headaches, minor injuries etc.) and routine physical exams. Patients with more complex care needs

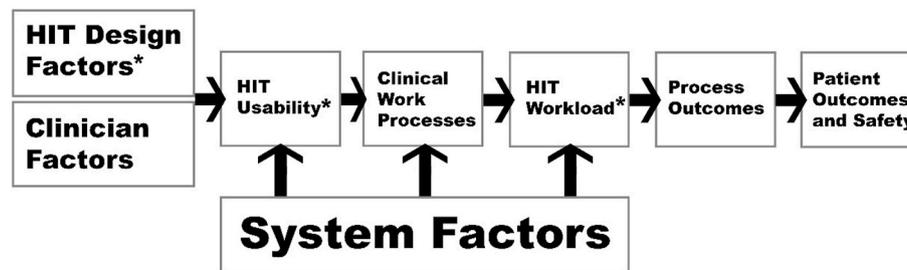


Fig. 1. Conceptual Model - Concepts measured in this study.

are referred to the primary care clinics and patients with serious acute illnesses are transferred to the emergency department. One of the clinics was slightly larger, serving 130–180 vs. 90–120 patients per day with slightly more staff.

## 2.2. Electronic health record systems

The study compared a hybrid- and a vendor (MU)-based EHR system. The hybrid system supported work in the urgent care centers during the pre-study period. In this system, paper was used for intake/chief complaint, clinical notes, medical orders and for writing patient information like vital signs before transcribing into the EHR. Provider (included MDs and Advance Practice Nurses) clinical notes were dictated to an outside transcription service. Many of the paper documents were scanned into the EHR at a later time. In summary, the EHR used in the pre-study period was primarily a scanned repository for documentation and rarely used during patient care.

The new EHR was supplied by a large vendor and was designed to meet the Center of Medicare and Medicaid's "Meaningful Use" objectives. Unlike the pre-study period, providers now entered medical orders, medications and clinic notes directly into this vendor EHR during and immediately after the patient visits. Nursing staff (included registered nurses and medical assistants) entered vital signs and clinic notes directly into the EHR during the patient visit. The vendor EHR also supported electronic prescribing, test ordering, and medication reconciliation. The change to the new EHR system also included additional computers in the patient exam rooms where much of the clinical documentation was expected to occur. In short, the vendor EHR system supported direct delivery and documentation of care to patients, and clinicians were able to search for specific patient data.

## 2.3. Participant sample

We used convenience sampling, advertising during staff meetings and via email. Because of the small number of clinicians employed at the sites, we grouped participants based on similar position responsibilities in these clinics: Nursing staff (RNs and medical assistants) and provider staff (MD and advanced practice nurses).

## 2.4. Measures

**Workload.** The NASA-TLX instrument (pencil and paper version) was used to assess perceived workload, that is, the perceived amount of mental processing capability required to perform clinical tasks in the EHR (Hart and Staveland, 1988; Nygren, 1991). The instrument includes six areas (mental demand, temporal demand, physical demand, perception of own performance, effort, and frustration level) that affect the responder's perception of workload (Becker et al., 1995; Hart and Staveland, 1988; Hendy et al., 1997). It performs well psychometrically (Cronbach's alphas >.80) and has been used extensively to study workload in aviation and other complex industries (Becker et al., 1995; Hendy et al., 1997) including the healthcare domain. (Bertram et al., 1992; Delacreataz and Frutiger, 1994; Dunn Lopez et al., 2010).

**Usability.** Perceived usability of the EHR interfaces was measured by the System Usability Scale, often used to measure usability of a broad range of device/system interfaces (Brooke, 1996). It is a 10-item Likert-type Scale (strongly agree to strongly disagree) survey that measures need for support, training, complexity, integration, ease of learning and confidence in use. It performs well psychometrically (coefficient alphas .7-.92) (Lewis, 1995; Lewis and Sauro, 2009). Because of its frequent use and broad application, it is considered an industry standard.

**Heuristic Evaluation.** Our Heuristic Evaluation tool was adapted from the tool for EHR Interface Expert Review, itself an expansion and application of Nielsen's heuristic review principles, to the use of EHRs to accomplish health care delivery tasks (Lowry et al., 2012). 92 items from this tool determined to be most relevant to the health tasks in the study setting were chosen and nested in Nielsen's 10 usability heuristic categories (Supplemental File 1). The evaluation focused on the two most common EHR tasks in this setting for each profession: Vital sign documentation and medication reconciliation for RN staff (Marien et al., 2019); clinical notes and clinical test ordering (Murphy et al., 2019) for Provider staff. Both professions had one "simpler" task that focused primarily on information entry (vital signs and clinical notes) and a task that required more steps (medication reconciliation and test ordering).

## 2.5. Data collection procedures

**Surveys.** Self-administered paper surveys (SUS and NASA-TLX) were collected during routine work shifts. Prior to participation, potential participants were given short explanations about the study, consent was obtained, and surveys were completed and returned to the research assistants.

**Heuristic Evaluation.** Following HE recommendations (Bias, 1991), we used a multi-disciplinary approach to evaluation. Two trained research assistants who were human factors students evaluated the interface screens of the vendor EHR individually in the order they would appear to workers using the interface to accomplish the four target health care tasks. Following recommendations for HE of EHR systems (Lowry et al., 2012), the evaluators were thoroughly trained on the purpose of the target tasks and the role of the EHR to accomplish these tasks before conducting the HE. Their training also included practice using the interface to accomplish the tasks at the health organization's EHR training center, as well as working with the setting's medical informatics expert who contributed domain knowledge to the RAs that enabled a greater understanding of the risk of harm associated with the usability problems. The human factors evaluation was supplemented by an independent analysis of the EHR interface by a clinical expert who was a clinician leader in Quality and Safety and familiar with the EHR but not a routine user.

## 2.6. Data analysis

**Surveys.** We computed and examined descriptive statistics for the SUS and NASA-TLX surveys at each time period of the study. Some of the providers and nurses participated in more than one phase. For purposes

of analyzing effects of phase (pre-implementation, 6-8- or 30-32-months post implementation) and role on SUS and TLX, participant performance in only one phase was included, resulting in a between-subjects design. Performance from the first phase that these participants completed was usually included. However, for some participants data from their second or third phase was included in an effort to balance the number of participants in each phase for the analysis.

The NASA-TLX, was scored by measuring the participant’s tally mark on the 1–10 visual analog scale for each item. Then following Hart (2006), unweighted raw TLX scores were averaged for each item (mental demand, temporal demand, physical activity, view of success, combined mental and physical effort, and frustration) and for overall workload (sum of each subscale rating per participant).

SUS scores were computed using the method developed by Brooks (1996). All scores were converted based on positive or negative item wording and scores were summed and then multiplied by 2.5 to convert the score from a 0–40 range to the standard 0–100 scale. The mean score across a broad range of studies is 68, which is considered an acceptable level of usability.

Scores per participant for each survey (SUS and TLX) were averaged by role (Provider vs RN staff) and phase (baseline before vendor EHR implementation, 6-8- and 30-32-months post implementation).

The first and second study aims were addressed by conducting separate Role (Provider versus RN) x Phase (pre-implementation, 6–8 months, 30–32 months) between-subject ANOVAs on EHR-related workload (TLX composite scores as well as subscale scores) and usability (SUS composite score). To address the third aim, we conducted linear regressions with workload ratings (TLX composite score and subscale scores) regressed on usability (SUS composite score). Role was entered first to control for the effect of this variable on usability. Data were analyzed using R © version 3.3.2.

**Heuristic Evaluation.** The fourth study aim was addressed by conducting an HE on the vendor EHR interface, using methods adapted from Nielsen and by Lowry et al., (2012) (Nielsen, 1993; Zhang et al., 2003). Each of the 92 items were scored from 0 to 3 (0 = no problem; 1 = cosmetic problem; 2 = minor usability problem; 3 = major usability problem, high priority to fix). In addition to problem severity, as recommended by Tang and colleagues, our ratings also took into account the impact, frequency, and persistence of the problem (Tang et al., 2006). For example, if a minor usability issue was so frequent and persistent that it created significant potential for usability issues, it was rated 3 rather than 2. Comments were included for items scored ≥1, which provided rationale for the score.

The research team’s senior human factors expert (DGM) reviewed the two human factor evaluators’ scores. Differences between the ratings were resolved by discussion to develop consensus. This yielded a single human factors expert score for each item. The clinical expert evaluator individually rated the interfaces for each task in order to validate the impact, frequency, and persistence of the problem.

2.7. Ethical considerations

This minimal-risk study was approved by the relevant Institutional Review Boards. Participation was voluntary. Each subject was given a unique study number such that names were not directly connected to the survey responses to minimize the chance of breach of confidentiality.

3. Results

3.1. Participant characteristics

Participants were 22 nursing staff (10 RNs and 12 medical assistants) and 13 provider staff (11 MDs, and 2 advanced practice nurses). The approximate response rate was 40%. Participant characteristics are reported in Table 1.

Table 1 Participant characteristics.

	Nursing Staff RNs (n = 22)	Provider Staff (n = 13)
Age (average/range)	32.5 (20–66)	45.3 (25–63)
Gender (% males)	10%	54%
<b>Ethnicity</b>		
• Asian	0	3 (23.1%)
• Black or African American	2 (9.1%)	1 (7.7%)
• Hispanic or Latino	1 (4.5%)	1 (7.7%)
• Native American/Alaska Native		1 (7.7%)
• White or Caucasian	18 (81.8%)	7 (53.8%)
• Multiple ethnicities	1 (4.5%)	
Years of Experience (average/range)	6.4 (0.2–22)	15.8 (1.5–30)
Years in current setting (average/range)	3.4 (0–10)	7.1 (1–26)
Years of experience with previous Hybrid EHR (average/range)	2.5 (0–9)	6.2 (0–26)

3.2. Workload and usability

Mean workload (composite NASA-TLX) and usability (SUS) ratings by study phase and professional role are depicted in Fig. 2.

For overall workload, the first prediction was supported by a significant effect of Phase ( $F(2,29) = 9.9, p < .001, \eta^2_p = .41$ ), with workload increasing for all participants after adoption of the vendor EHR (Baseline < 6 months and 18 months). A non-significant difference between the two post-implementation time points suggested the increased workload associated with adopting the vendor EHR persisted over two years. The second prediction, related to differences in Provider and RN workload, was not supported. Although there was a numeric trend suggesting Provider participants perceived higher workload than RN participants did (27.1 versus 21.1), this difference did not reach significance ( $F(1,29) = 3.1, p = 0.08, \eta^2_p = 0.10$ ). The planned comparison between Provider ( $m = 35.9$ ) and RN ( $m = 27.0$ ) workload at 6 months was not significant ( $t(11) = 1.3, p > .10, \text{Cohen's } d = 2.24$ ). The Role x Phase interaction was not significant ( $F(2,29) = 0.2, p > .10, \eta^2_p = 0.01$ ).

To further explore the effects of Role and Phase on workload, we conducted ANOVAs on the six TLX subscales. Table 2 shows that the impact of Phase was robust, with the same pattern as for the composite score occurring for all subscales except physical activity. The analyses of

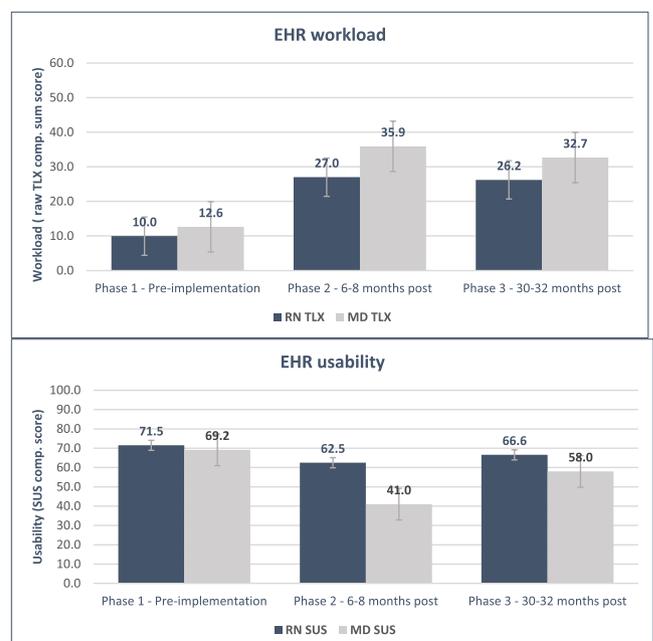


Fig. 2. Mean overall workload and usability by role across study phase.

**Table 2**  
Workload subscales by role across study phase.

NASA Task Load Index (NASA-TLX)	Pre-implementation			6–8 months post			30–32 months post			Grand Mean
	RNs	PRVDs	Mean	RNs	PRVDs	Mean	RNs	PRVDs	Mean	
Mental Demand	1.7	2.2	1.9	5.2	6.5	5.7	4.1	5.4	4.6	4.4
Temporal Demand	1.9	2.5	2.1	5.3	7.2	6.0	4.8	6.9	5.6	5.0
Physical Activity	1.9	2.4	2.1	3.1	2.5	2.9	3.0	3.2	3.1	2.8
View of Success	0.7	1.2	0.9	4.2	5.6	4.7	4.0	5.9	4.7	3.8
Combined Effort	2.4	2.1	2.3	5.6	6.7	6.0	6.3	7.3	6.6	5.4
Frustration	1.4	2.2	1.7	3.6	7.5	5.0	4.1	4.0	4.1	3.9
<b>TLX Composite</b>	<b>10.0</b>	<b>12.6</b>	<b>11.0</b>	<b>27.0</b>	<b>35.9</b>	<b>30.2</b>	<b>26.2</b>	<b>32.7</b>	<b>28.7</b>	<b>25.2</b>

**Table 3**  
Regression analysis for variables associated with NASA TLX workload ratings.

Composite score:						
Variables	B	SE β	t-test	β	SE β	t-test
Role				2.32	4.07	0.57
Usability	−0.36	0.10	−3.74 ***	−0.34	0.10	−3.36 **
R <sup>2</sup>	0.30			0.30		
F for change in R <sup>2</sup>	0.33					
Usability:						
Subscales	cor	β	SE β	t-test		
Mental Demand	−.56 ***	−0.08	0.02	−3.90 ***		
Temporal Demand	−.56 ***	−0.07	0.02	−3.85 ***		
Physical Activity	−.35 *	−0.04	0.02	−2.11 *		
View of Success	−.28	−0.04	0.03	−1.66		
Combined Effort	−.29 †	−0.04	0.02	−1.73 †		
Frustration	−.61 ***	−0.08	0.02	−4.39 ***		

Note: †p < .10; \*p < .05; \*\*p < .01; \*\*\*p < .001.

the subscales provided some evidence for the second prediction: providers experienced higher temporal demands ( $F(1,29) = 5.4, p = 0.03, \eta^2_p = 0.16$ ) and more frustration ( $F(1,29) = 5.7, p = .02, \eta^2_p = 0.17$ ) than RNs did, and this increase was primarily at 6 months for frustration ( $F(2,29) = 3.7, p = .03, \eta^2_p = 0.20$ ).

Because of the small sample size in the study, we also conducted the Levene’s Test for Homogeneity of Variance and nonparametric versions of the above analyses (Scheirer-Ray-Hare and Wilcoxon-Mann-Whitney tests). We do not report these results because both the workload (TLX composite scores) and the usability (SUS composite score) data did not violate the assumptions of homogeneity of variances (workload: ( $F(1,29) = 1.0, p > .10$ ; usability: ( $F(1,29) = 0.6, p > 0.10$ ) and the pattern of findings was unchanged in the nonparametric analyses.

Analysis of the EHR-related usability scores provided some evidence that physician workload may be due in part to inadequate usability. The effect of Role ( $F(1,29) = 3.5, p = 0.07, \eta^2_p = .11$ ) and Phase ( $F(2,29) = 2.0, p > .10, \eta^2_p = .12$ ) did not reach significance. Because we predicted that usability would be lower for Provider than for RN participants immediately after adoption of the vendor EHR, we conducted a planned comparison between Provider and RN usability scores at the 6–8 month time period (Phase 2) even though the Role  $\times$  Phase interaction was not significant ( $F(2,29) = 0.7, p > .10, \eta^2_p = .05$ ) (Wickens and Keppel, 2004). A Welch’s unequal variances *t*-test showed that Provider usability ratings were lower (worse usability) compared to RN ratings ( $t(5) = 2.2, p < .05, \text{Cohen’s } d = 3.13$ ). The mean score of 41 is well below the average of 68 found in many studies using SUS ( $t(4) = 2.9, p < .05, \text{Cohen’s } d = 1.97$ ). Thus, there was some evidence for the first prediction (reduced usability immediately post-adoption) but only for providers. Consistent with the second prediction, providers experienced lower usability than RNs immediately post-adoption.

The third prediction was evaluated by conducting linear regressions with workload ratings (TLX subscales and composite score) regressed on usability (SUS composite score). Role was first entered the model to control for effects of this variable on usability.

Table 3 shows that, consistent with the third prediction and our model (Fig. 1), overall workload was associated with EHR usability

(lower usability associated with higher workload), independent of role-related effects on usability. Lower usability was associated with increased mental demand, temporal demand, frustration and physical activity.

### 3.3. Heuristic Evaluation

The HE analysis suggested potential sources of usability declines and workload increases after MU-EHR adoption. Table 4 summarizes the HE results in terms of the percentage of items within each of the 10 heuristic categories that were rated as 0, 1, 2, or 3 by the consensus of the human factors (HF) experts and by the clinician (C) expert, averaged across the two nursing tasks and the two provider tasks. Overall agreement between the HF and the C expert was about 60% across all 92 items. Twenty-four of the items were rated as a major usability problem by the HF, clinician or both experts. These violations were present in all but three of the heuristic categories (Aesthetic and Minimal Design, User Control and Freedom, and Help and Documentation). To provide additional context, representative examples of heuristic violations for each professions’ tasks are presented in Table 5.

The violations varied by task. There were 13 major usability violations for the two physician tasks compared to seven for the two nursing tasks. The physician task of ordering clinical tests had the highest number of violations across the four tasks. On the other hand, vital sign entry for nurses had the fewest violations across tasks, perhaps reflecting the relative simplicity of this task.

## 4. Discussion

Over a decade after the Meaningful Use incentive program was enacted, poor usability and workload associated with electronic health records continues to be a major concern among clinicians (Boyle et al., 2019; Hudson et al., 2018; Melnick et al., 2019). In this mixed methods study, we found usability and workload issues following the change to a MU persisted for at least two and a half years for both physicians and nurses. Although other pre-post studies exist, this is the longest study of

**Table 4**  
Heuristic violations identified by human factors and clinical experts across all clinical tasks.

Category	Score	% Violations - Nurse tasks		% Violations - Physician tasks	
		Human Factors	Clinician	Human Factors	Clinician
<b>Visibility of system status</b>	0 - No Violation	28%	94%	56%	83%
	1 - Cosmetic Issue	22%	0%	22%	17%
	2 - Minor Usability Issues	44%	6%	22%	0%
	3 - Major Usability Issue	6%	0%	0%	0%
<b>Match between system and the real world</b>	0 - No Violation	57%	50%	50%	79%
	1 - Cosmetic Issue	7%	0%	7%	21%
	2 - Minor Usability Issues	21%	50%	36%	0%
	3 - Major Usability Issue	14%	0%	7%	0%
<b>User control and freedom</b>	0 - No Violation	72%	89%	83%	61%
	1 - Cosmetic Issue	0%	0%	0%	11%
	2 - Minor Usability Issues	28%	11%	17%	28%
	3 - Major Usability Issue	0%	0%	0%	0%
<b>Consistency and Standards</b>	0 - No Violation	64%	100%	68%	82%
	1 - Cosmetic Issue	18%	0%	11%	18%
	2 - Minor Usability Issues	18%	0%	18%	0%
	3 - Major Usability Issue	0%	0%	4%	0%
<b>Recognition rather than recall</b>	0 - No Violation	67%	72%	78%	50%
	1 - Cosmetic Issue	6%	6%	6%	22%
	2 - Minor Usability Issues	22%	6%	6%	6%
	3 - Major Usability Issue	6%	17%	11%	22%
<b>Flexibility and efficiency of use</b>	0 - No Violation	88%	94%	81%	38%
	1 - Cosmetic Issue	0%	0%	0%	44%
	2 - Minor Usability Issues	13%	6%	6%	19%
	3 - Major Usability Issue	0%	0%	13%	0%
<b>Aesthetic and minimalist design</b>	0 - No Violation	42%	83%	67%	83%
	1 - Cosmetic Issue	0%	17%	17%	17%
	2 - Minor Usability Issues	58%	0%	17%	0%
	3 - Major Usability Issue	0%	0%	0%	0%
<b>Help users recognize, diagnose, and recover from errors</b>	0 - No Violation	35%	80%	55%	60%
	1 - Cosmetic Issue	10%	0%	5%	20%
	2 - Minor Usability Issues	55%	20%	30%	20%
	3 - Major Usability Issue	0%	0%	10%	0%
<b>Help and documentation</b>	0 - No Violation	33%	83%	58%	67%
	1 - Cosmetic Issue	33%	0%	8%	0%
	2 - Minor Usability Issues	33%	17%	33%	33%
	3 - Major Usability Issue	0%	0%	0%	0%
<b>Error prevention</b>	0 - No Violation	75%	89%	75%	75%
	1 - Cosmetic Issue	4%	0%	0%	11%
	2 - Minor Usability Issues	21%	11%	25%	11%
	3 - Major Usability Issue	0%	0%	0%	4%

this type we were able to identify. We note that usability ratings were trending toward pre-implementation levels at 30 months, suggesting that over a longer period of time EHR usability may have recovered. Nonetheless, this reflects a substantial interval of time of reduced usability.

#### 4.1. Long-lasting impact of EHR system changes on clinician workload

We found that EHR workload more than doubled six months following EHR change, with no significant improvement 30 months later. This pattern held for all workload subscales except physical activity, suggesting EHR adoption primarily increased cognitive workload, presumably in part because the EHR was now used to deliver patient care during visits rather than to document care after these visits. The persistent effects of EHR use on this cognitive workload was associated with decreased EHR usability. Our framework and the literature suggest that decreased usability in turn reflects design features of the MU-EHR system. Carayon and colleagues (2015) for example, found that identifying and clicking into multiple fields to find and enter discrete patient information is more difficult than either paper or dictation-based documentation (Carayon et al., 2015). Ahmed et al. (2011) compared a standard EHR interface to one that was designed to display high priority information near the top of the screen. They found that this design improvement significantly reduced cognitive workload and increased time efficiency. Our HE analysis suggested potential sources of limited usability by identifying design violations that may reduce the ease of

learning and using the system. For example, “Match between System and World” may reduce ability to draw upon previous knowledge to help learn the system. “Visibility of the System Status” can impair awareness of which step in a multi-step process the user is currently in, or whether the system is processing a command or is ready for the next command. In addition, violations related to “Help/Documentation” make it difficult to learn how to address problems without the help of an expert. The impact of such design-related problems on clinical workload is likely to be magnified by increased need to use MU-EHRs to accomplish most clinical tasks, compared to earlier generation EHRs.

#### 4.2. Provider versus nurse workload

We predicted that providers would experience greater increases in workload associated with the adoption of a MU-EHR system compared to RNs. In support of this prediction, analysis of the NASA-TLX subscales revealed increased Provider ratings for frustration and time pressure components of workload post-adoption. This pattern is consistent with the increased amount of EHR-based work that providers must perform in the MU environment. The temporal demand effects may be driven by the fact that providers now use the EHR when seeing patients. The frustration-related effects validate providers’ concerns about stress and time pressure. The EHR usability and HE findings suggest that increased EHR-based work exposes providers to EHR design-related problems that in turn magnify their workload.

It is important to point out that although the RNs reported better

**Table 5**  
Examples of Violations identified by Experts across tasks.

	Nurse tasks	Physician tasks
<b>Visibility of system status</b>	Abbreviated headers do not adequately convey screen content. Selected items are not adequately highlighted.	There is no feedback for actions. (e.g. clinician mouse clicks but the system does not respond)
<b>Match between system and the real world</b>	Icons are non-intuitive and not unique. (e.g. wrench and magic wand are both used as editing icon)	The alert for "1 unsigned order" is green while, when yellow or red are expected alert colors
<b>User control and freedom</b>	Often the keyboard shortcuts do not work as a navigation aid	There is no Undo option
<b>Consistency and standards</b>	Icons are inconsistently used for different tasks	Keyboard shortcuts are different across contexts (e.g. space bar is used to move to next section instead of tab)
<b>Recognition rather than recall</b>	Complex dose info/instructions are not always apparent	Required fields are not differentiated from optional fields
<b>Flexibility and efficiency of use</b>	Information about alerts is not easy to find	Multiple clicks needed to edit information, where keyboard would be more efficient
<b>Aesthetic and minimalist design</b>	Disorganized, unclear interface, poor visual demarcation between discrete components	Pop-up/pull-down menus have many options
<b>Help users recognize, diagnose, and recover from errors</b>	There is no warning for unusual dose. (e.g. allows dispensing 100,000 tablets)	Recovering from errors is not easy. (e.g. need to remove an entry to get rid of an error message)
<b>Help and documentation</b>	Insufficient ways to find the help section.	No context-sensitive help
<b>Error prevention</b>	Unable to track copied text.	Allows entry of free text that does not match other fields

EHR usability compared to providers, this does not mean the parts of the EHR most used by nurses can be considered well-designed. To the contrary, Bangor et al. (2009) used a large sample of SUS data to develop an adjective rating scale for usability that correlates highly with SUS scores ( $r = 0.822$ ) (Bangor et al., 2009). Using this scale, the RNs' perceived usability for the new EHR (both phases) was considered marginal. Similar to our finding, they also found providers' rating of unacceptable as worse than nurses' rating. The frequency of minor and major usability violations for nursing tasks identified in our HE supports this finding. Thus, it is important to keep in mind, when examining trends, increasing usability scores may not mean the technology is optimal or even acceptable. More recently, Wisner et al. (2019) found that EHRs have a major impact on nurses' cognitive work and at times were an impediment to synthesizing information.

#### 4.3. Implications for improving clinical workload related to EHR use

We identified several heuristic violations that are likely related to the clinicians' perceptions of poor usability and workload. Thankfully, the majority of these violations were considered minor or cosmetic issues and therefore unlikely to represent a major threat to patient safety. Although the violations were rated as minor, the combination of the number of violations along with the pervasiveness of EHR work in healthcare contributes to the overall time demands and difficulty completing tasks.

It is important to note that these findings do not, by itself, provide adequate guidance for modifying the EHR to improve usability and workload. A larger-scale study involving multiple methods across multiple tasks (observation, interview, and other qualitative measures in addition to HE and surveys) is needed to better understand the users,

environment and workflow (Schumacher, Lowry and Technology, 2010). However, as Savoy and colleagues demonstrated (2018), with additional data, human factors principles can be used to translate and redesign interfaces for clinicians that result in improved task efficiency and usability (Savoy et al., 2018).

We concur with others that have demonstrated the important role that redesign can have on clinicians' workload (Fuller et al., 2020; Pierce et al., 2020) and the need for human factors in clinical practice (Beasley et al., 2020). In addition, EHR vendors need mechanisms for addressing end-user identified usability problems. Our informal discussions with clinical leaders have suggested that although these mechanisms exist, the sheer volume of requests for changes and improvement may draw out the timeline for any modification to be realized. Perhaps better usability testing with real end users before implementation would decrease these requests (Carayon et al., 2006). (HITECH Act, 2010) (LOPEZ).

We also believe clinicians at all levels should have some formal education to help them identify, report, and articulate EHR usability problems (Lopez and Fahey, 2018). Organizations should also have strong and transparent EHR governance processes to ensure requested changes are prioritized and vetted for unintended consequences. Despite the important role clinicians and organizations can and should play in improving the EHR safety net, we place the lion's share of responsibility on the EHR vendors whose product may cost individual health systems upwards of \$1 billion dollars (Cohen, 2017; McCluskey, 2016) and indirectly on government agencies who can set incentives to improve EHR usability.

#### 4.4. Limitations

This study took advantage of a 'natural experiment' associated with organizational change (adopting a new large-scale EHR), with a pre-set go-live date. This type of study has several methodological limitations common to field-based data collection studies in health care work environments (Holden et al., 2011; Koppel et al., 2008; Saleem et al., 2005). First, in this voluntary study, convenience sampling may have yielded a biased sample. For example, clinicians with the most negative perception of usability may have declined participation and a random sample may have resulted in even lower usability scores. Second, our population was small, and the response rate less than 50%, yielding a small sample size. A larger study is needed to repeat this research in a fully powered sample. Third, very few participants were available to participate in all 3 phases, preventing within-subject analyses over time. Fourth, we note EHR underwent two system upgrades between the second and third phase of the study. These upgrades addressed overall EHR functionality and improvements in documentation and ordering capabilities. Such efficiencies did not reduce provider and staff workload volumes but could have improved usability for those providers who took advantage of the upgraded features. It is also possible that the upgrades unintentionally added new work. A fifth possible limitation of the study is that the SUS and NASA-TLX surveys were administered to participants during breaks in patient care, creating a short lag between task performance and completing the measure that could have influenced the reliability of the measurement.

#### Summary

In one of the longest studies of clinician adaptation to a MU-EHR, we found that clinicians, especially provider staff, experienced long lasting perceptions of increased workload and decreased usability after adoption of a MU-EHR system. The finding that usability ratings predicted workload suggests the importance of policies and incentives for vendors to improve the usability of their systems, which in turn should improve overall patient safety given the widespread adoption of EHRs.

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## In Memoriam

We dedicate this paper to our co-author William Schuh, who died tragically in October. Bill's cheerful professionalism, expertise in health informatics, and warmth made him an ideal collaborator. He will be greatly missed by us and his many colleagues and friends.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

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## References

- Ackerman, P.L., 1988. Determinants of individual differences during skill acquisition: cognitive abilities and information processing. *J. Exp. Psychol. Gen.* 117 (3), 288.
- Ahmed, A., Chandra, S., Herasevich, V., Gajic, O., Pickering, B.W., 2011. The effect of two different electronic health record user interfaces on intensive care provider task load, errors of cognition, and performance. *Crit. Care Med.* 39 (7), 1626–1634. <https://doi.org/10.1097/CCM.0b013e31821858a0>.
- Ancker, J.S., Kern, L.M., Edwards, A., Nosal, S., Stein, D.M., Hauser, D., Kaushal, R., 2015. Associations between healthcare quality and use of electronic health record functions in ambulatory care. *J. Am. Med. Inf. Assoc.* 22 (4), 864–871. <https://doi.org/10.1093/jamia/ocw030>.
- Ariza, F., Kalra, D., Potts, H.W., 2015. How do clinical information systems affect the cognitive demands of general practitioners?: usability study with a focus on cognitive workload. *J. Innovat. Health Inf.* 22 (4), 379–390.
- Arndt, B.G., Beasley, J.W., Watkinson, M.D., Temte, J.L., Tuan, W.-J., Sinsky, C.A., Gilchrist, V.J., 2017. Tethered to the EHR: primary care physician workload assessment using EHR event log data and time-motion observations. *Ann. Fam. Med.* 15 (5), 419–426.
- Bangor, A., Kortum, P., Miller, J., 2009. Determining what individual SUS scores mean: adding and adjective rating scale. *Journal of usability studies* 4 (3), 114–123.
- Beasley, J.W., Holden, R.J., Ötles, E., Green, L.A., Steege, L.M., Wetterneck, T.B., 2020. It's time to bring human factors to primary care policy and practice. *Appl. Ergon.* 85, 103077.
- Becker, A., Warm, J., Dember, W., 1995. Effects of jet engine noise and performance feedback on workload in a monitoring task. *Int. J. Aviat. Psychol.* 5, 49–62.
- Benda, N.C., Meadors, M.L., Hettinger, A.Z., Ratwani, R.M., 2016. Emergency physician task switching increases with the introduction of a commercial electronic health record. *Ann. Emerg. Med.* 67 (6), 741–746.
- Berner, E.S., Detmer, D.E., Simborg, D., 2005. Will the wave finally break? A brief view of the adoption of electronic medical records in the United States. *J. Am. Med. Inf. Assoc.* 12 (1), 3–7. <https://doi.org/10.1197/jamia.M1664>.
- Bertram, D., Opilia, D., Brown, J., 1992. Measuring physician mental workload-reliability and validity assessment of a brief instrument. *Med. Care* 30, 95–104.
- Bias, R., 1991. Interface-Walkthroughs: efficient collaborative testing. *IEEE Software* 8 (5), 94–95.
- Blijleven, V., Koelemeijer, K., Wetzels, M., Jaspers, M., 2017. Workarounds emerging from electronic health record system usage: consequences for patient safety, effectiveness of care, and efficiency of care. *JMIR Human Factors* 4 (4), e27.
- Boyle, D.K., Baerholdt, M., Adams, J.M., McBride, S., Harper, E., Poghosyan, L., Manges, K.J. N.o., 2019. Improve nurses' well-being and joy in work: implement true interprofessional teams and address electronic health record usability issues, 67 (6), 791–797.
- Brooke, J., 1996. SUS-A quick and dirty usability scale. *Usability evaluation in industry* 189 (194), 4–7.
- Carayon, P., Hundt, A.S., Hoonakker, P., 2019. Technology barriers and strategies in coordinating care for chronically ill patients. *Appl. Ergon.* 78, 240–247. <https://doi.org/10.1016/j.apergo.2019.03.009>.
- Carayon, P., Hundt, A., Karsh, B., Gurses, A., Alvarado, C., Smith, M., Brennan, P., 2006. Work system design for patient safety: the SEIPS model. *Qual. Saf. Health Care* 15 (Suppl. 1), i50–i58.
- Carayon, P., Wetterneck, T.B., Alyousef, B., Brown, R.L., Cartmill, R.S., McGuire, K., Hoonaker, P.L., Slagle, J., Van Roy, K.S., Walker, J.M., 2015. Impact of electronic health record technology on the work and workflow of physicians in the intensive care unit. *Int. J. Med. Inf.* 84 (8), 578–594.
- Carayon, P., Wooldridge, A., Hoonakker, P., Hundt, A.S., Kelly, M.M., 2020. Seips 3.0: human-centered design of the patient journey for patient safety. *Appl. Ergon.* 84, 103033.
- Cohen, J., 2017. 10 EHR Implementation with the Biggest Pricetags in 2017. *Becker's Health IT and CIO Report.* (December 18).
- Colligan, L., Potts, H.W., Finn, C.T., Sinkin, R.A., 2015. Cognitive workload changes for nurses transitioning from a legacy system with paper documentation to a commercial electronic health record. *Int. J. Med. Inf.* 84 (7), 469–476.
- Delacreataz, A., Frutiger, P., 1994. Nursing summary and experienced workload. *Comput. Methods Progr. Biomed.* 43, 177–183.
- Dunn Lopez, K., Gerling, G., Cary, M., Kanak, M., 2010. Cognitive work analysis to evaluate the problem of patient fall in an inpatient setting. *J. Am. Med. Inf. Assoc.* 17, 313–321.
- Fuller, T.E., Garabedian, P.M., Lemonias, D.P., Joyce, E., Schnipper, J.L., Harry, E.M., Bates, D.W., Dalal, A.K., Benneyan, J.C., 2020. Assessing the cognitive and workload of an inpatient safety dashboard in the context of opioid management. *Appl. Ergon.* 85, 103047.
- Gardner, E., 2015. Frustrations with EHRs rampant as development slows. *ACP Internist.* Retrieved from. <https://www.acponline.org/acp-newsroom/new-survey-offers-insight-on-efforts-to-improve-ehr-usability>.
- Gardner, R.L., Cooper, E., Haskell, J., Harris, D.A., Poplau, S., Kroth, P.J., Linzer, M., 2019. Physician stress and burnout: the impact of health information technology. *J. Am. Med. Inf. Assoc.* 26 (2), 106–114.
- Gawande, A., 2018. Why Doctors Hate Their Computers. *The New York Times.* (Nov. 12).
- Gephart, S., Carrington, J.M., Finley, B., 2015. A systematic review of nurses' experiences with unintended consequences when using the electronic health record. *Nurs. Adm. Q.* 39 (4), 345–356.
- Hanauer, D.A., Branford, G.L., Greenberg, G., Kileny, S., Couper, M.P., Zheng, K., Choi, S.W., 2016. Two-year longitudinal assessment of physicians' perceptions after replacement of a longstanding homegrown electronic health record: does a J-curve of satisfaction really exist? *J. Am. Med. Inf. Assoc.* 24 (e1), e157–e165.
- Hanauer, D.A., Branford, G.L., Greenberg, G., Kileny, S., Couper, M.P., Zheng, K., Choi, S.W., 2016. Two-year longitudinal assessment of physicians' perceptions after replacement of a longstanding homegrown electronic health record: does a J-curve of satisfaction really exist? *J. Am. Med. Inf. Assoc.* 24 (e1), e157–e165. <https://doi.org/10.1093/jamia/ocw077>, 2017 Apr 1.
- Hart, S.G., 2006. NASA-task load Index (NASA-TLX); 20 Years later. In: *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*, 904–908. Santa Monica: HFES.
- Hart, S., Staveland, L., 1988. Development of NASA TLX (task load Index): results of empirical and theoretical research. In: Hancock, P., Meshkati, N. (Eds.), *Human Mental Workload*. North Holland Press, Amsterdam.
- Hendy, K., Liao, J., Milgram, P., 1997. Combining time and intensity effects in assessing operator information processing load. *Hum. Factors* 39, 30–47.
- HITECH Act, 2010. *Health Information Technology for Economic and Clinical Health*. 123 Stat. 226–276, Public Law 111-5 Feb. 17, 2009. In: H.
- Holden, R.J., Brown, R.L., Alper, S.J., Scanlon, M.C., Patel, N.R., Karsh, B.-T., 2011. That's nice, but what does IT do? Evaluating the impact of bar coded medication administration by measuring changes in the process of care. *Int. J. Ind. Ergon.* 41 (4), 370–379.
- Howe, J.L., Adams, K.T., Hettinger, A.Z., Ratwani, R.M., 2018. Electronic health record usability issues and potential contribution to patient harm. *J. Am. Med. Assoc.* 319 (12), 1276–1278.
- Hudson, D., Kushniruk, A., Borycki, E., Zuege, D.J., 2018. Physician satisfaction with a critical care clinical information system using a multimethod evaluation of usability. *Int. J. Med. Inf.* 112, 131–136.
- Hyman, D., Neiman, J., Rannie, M., Allen, R., Swietlik, M., Balzer, A., 2017. Innovative use of the electronic health record to support harm reduction efforts. *Pediatrics* 139 (5), e20153410.
- Kern, L.M., Barrón, Y., Dhopeswarkar, R.V., Edwards, A., Kaushal, R., 2013. Electronic health records and ambulatory quality of care. *J. Gen. Intern. Med.* 28 (4), 496–503. <https://doi.org/10.1007/s11606-012-2237-8>.
- Kim, M.O., Coiera, E., Magrabi, F., 2017. Problems with health information technology and their effects on care delivery and patient outcomes: a systematic review. *J. Am. Med. Inf. Assoc.* 24 (2), 246–250. <https://doi.org/10.1093/jamia/ocw154>.
- Kjeldskov, J., Skov, M.B., Stage, J., 2010. A longitudinal study of usability in health care: does time help? *Int. J. Med. Inf.* 79 (6), e135–e143.
- Koppel, R., Wetterneck, T., Telles, J.L., Karsh, B.-T., 2008. Workarounds to barcode medication administration systems: their occurrences, causes, and threats to patient safety. *J. Am. Med. Inf. Assoc.* 15 (4), 408–423.
- Krousel-Wood, M., McCoy, A.B., Ahia, C., Holt, E.W., Trapani, D.N., Luo, Q., Milani, R.V., 2018. Implementing electronic health records (EHRs): health care provider perceptions before and after transition from a local basic EHR to a commercial comprehensive EHR. *J. Am. Med. Inf. Assoc.* 25 (6), 618–626.
- Landman, A.B., Takhar, S.S., Wang, S.L., Cardoso, A., Kosowsky, J.M., Raja, A.S., Poon, E.G., 2013. The hazard of software updates to clinical workstations: a natural

- experiment. *J. Am. Med. Inf. Assoc.* 20 (e1), e187–e190. <https://doi.org/10.1136/amiajnl-2012-001494>.
- Lewis, J.R., 1995. IBM computer usability satisfaction questionnaires: psychometric evaluation and instructions for use. *Int. J. Hum. Comput. Interact.* 7 (1), 57–78.
- Lewis, J.R., Sauro, J., 2009. The factor structure of the system usability scale. Paper Presented at the International Conference on Human Centered Design. Springer, Berlin, Heidelberg, pp. 94–103.
- Lopez, K.D., Fahey, L., 2018. Advocating for greater usability in clinical technologies: the role of the practicing nurse. *Crit. Care Nurs. Clin* 30 (2), 247–257.
- Lowry, S.Z., Quinn, M.T., Ramaiah, M., Schumacher, R.M., Patterson, E.S., North, R., Abbott, P., 2012. Technical Evaluation, Testing, and Validation of the Usability of Electronic Health Records. National Institute of Standards and Technology.
- Mamykina, L., Vawdrey, D.K., Hripcsak, G., 2016. How do residents spend their shift time? A time and motion study with a particular focus on the use of computers. *Acad. Med.* 91 (6), 827–832.
- Marién, S., Legrand, D., Ramdoyal, R., Nsenga, J., Ospina, G., Ramon, V., Spinewine, A., 2019. A User-Centered design and usability testing of a web-based medication reconciliation application integrated in an eHealth network. *Int. J. Med. Inf.* 126, 138–146.
- McCluskey, P., 2016. New \$1.2 Billion Partners Computer System Brings Prescription for Frustration. *The Boston Globe*. (May, 16).
- Meeks, D.W., Smith, M.W., Taylor, L., Sittig, D.F., Scott, J.M., Singh, H., 2014. An analysis of electronic health record-related patient safety concerns. *J. Am. Med. Inf. Assoc.* 21 (6), 1053–1059. <https://doi.org/10.1136/amiajnl-2013-002578>.
- Melnick, E.R., Dyrbye, L.N., Sinsky, C.A., Trockel, M., West, C.P., Nedelec, L., Shanafelt, T., 2019. The association between perceived electronic health record usability and professional burnout among US physicians. In: Paper Presented at the Mayo Clinic Proceedings.
- Menon, S., Murphy, D.R., Singh, H., Meyer, A.N., Sittig, D.F., 2016. Workarounds and test results follow-up in electronic health record-based primary care. *Appl. Clin. Inf.* 7, 543–559, 02.
- Murphy, D.R., Satterly, T., Rogith, D., Sittig, D.F., Singh, H., 2019. Barriers and facilitators impacting reliability of the electronic health record-facilitated total testing process. *Int. J. Med. Inf.* 127, 102–108.
- National Institutes of Health, 2006. Electronic health records overview. National Center for Research Resources. National Institutes of Health, Bethesda.
- Nielsen, J., 1993. Usability heuristics. In: Nielsen, J. (Ed.), *Usability Engineering*. Academic Press, San Diego, CA, pp. 115–155.
- Nuckols, T.K., Smith-Spangler, C., Morton, S.C., Asch, S.M., Patel, V.M., Anderson, L.J., Shekelle, P.G., 2014. The effectiveness of computerized order entry at reducing preventable adverse drug events and medication errors in hospital settings: a systematic review and meta-analysis. *Syst. Rev.* 3 (1), 56.
- Nygren, T., 1991. Psychometric properties of subjective workload measurement techniques: implications for their use in the assessment of perceived mental workload. *Hum. Factors* 33 (1), 17–33.
- Pierce, R.P., Eskridge, B.R., Rehard, L., Ross, B., Day, M.A., Belden, J.L., 2020. The effect of electronic health record usability redesign on annual screening rates in an ambulatory setting. *Appl. Clin. Inf.* 11, 580–588, 04.
- Ryan, M.S., Shih, S.C., Winther, C.H., Wang, J.J., 2014. Does it get easier to use an EHR? Report from an urban regional extension center. *J. Gen. Intern. Med.* 29 (10), 1341–1348.
- Saleem, J.J., Herout, J., 2018. Transitioning from one Electronic Health Record (EHR) to another: a narrative literature review. In: Paper Presented at the Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 62, pp. 489–493, 1.
- Saleem, J.J., Patterson, E.S., Militello, L., Render, M.L., Orshansky, G., Asch, S.M., 2005. Exploring barriers and facilitators to the use of computerized clinical reminders. *J. Am. Med. Inf. Assoc.* 12 (4), 438–447.
- Savoy, A., Patel, H., Flanagan, M.E., Daggy, J.K., Russ, A.L., Weiner, M., 2018. Comparative usability evaluation of consultation order templates in a simulated primary care environment. *Appl. Ergon.* 73, 22–32. <https://doi.org/10.1016/j.apergo.2018.05.013>.
- Schulte, F., Fry, E., 2019. Death by 1,000 Clicks: where Electronic Health Records Went Wrong. *Kaiser Health News*, (March, 18).
- Schumacher, R.M., Lowry, S., 2010. NIST Guide to the Processes Approach for Improving the Usability of Electronic Health Records. US Department of Commerce, National Institute of Standards and Technology.
- Shanafelt, T.D., Dyrbye, L.N., Sinsky, C., Hasan, O., Satele, D., Sloan, J., West, C.P., 2016. Relationship between clerical burden and characteristics of the electronic environment with physician burnout and professional satisfaction. In: Paper Presented at the Mayo Clinic Proceedings.
- Sheehy, A.M., Weissburg, D.J., Dean, S.M., 2014. The role of copy-and-paste in the hospital electronic health record. *JAMA internal medicine* 174 (8), 1217–1218. <https://doi.org/10.1001/jamainternmed.2014.2110>.
- Sinsky, C., Colligan, L., Li, L., Prgomet, M., Reynolds, S., Goeders, L., Blike, G., 2016. Allocation of physician time in ambulatory practice: a time and motion study in 4 specialties. *Ann. Intern. Med.* 165 (11), 753–760.
- Tai-Seale, M., Olson, C.W., Li, J., Chan, A.S., Morikawa, C., Durbin, M., Luft, H.S., 2017. Electronic health record logs indicate that physicians split time evenly between seeing patients and desktop medicine. *Health Aff.* 36 (4), 655–662.
- Tang, Z., Johnson, T.R., Tindall, R.D., Zhang, J., 2006. Applying heuristic evaluation to improve the usability of a telemedicine system. *Telemed. J. e Health* 12 (1), 24–34.
- The Office for the National Coordinator of Health Information Technology, 2016. Non-federal acute care hospital electronic health record adoption, health IT quick-stat #47 retrieved from. <http://dashboard.healthit.gov/quickstats/pages/FIG-Hospital-EHR-Adoption.php>.
- Venkatesh, V., Davis, F.D., 2000. A theoretical extension of the technology acceptance model: four longitudinal field studies. *Manag. Sci.* 46 (2), 186–204.
- Walker, R.M., Burmeister, E., Jeffrey, C., Birgan, S., Garrahy, E., Andrews, J., Hada, A., Aitken, L.M., 2020. The impact of an integrated electronic health record on nurse time at the bedside: a pre-post continuous time and motion study. *Collegian* 27 (1), 63–74.
- Wickens, T.D., Keppel, G., 2004. *Design and Analysis: A Researcher's Handbook*. Pearson Prentice-Hall.
- Wisner, K., Lyndon, A., Chesla, C.A., 2019. The electronic health record's impact on nurses' cognitive work: an integrative review. *Int. J. Nurs. Stud.* 94, 74–84.
- Willyard, 2020. Electronic health records need a shot in the arm. *Scientific American*, (February 1). <https://www.scientificamerican.com/article/electronic-health-records-need-a-shot-in-the-arm/>.
- Wright, A., Hickman, T.-T.T., McEvoy, D., Aaron, S., Ai, A., Andersen, J.M., Bates, D.W., 2016. Analysis of clinical decision support system malfunctions: a case series and survey. *J. Am. Med. Inf. Assoc.* 23 (6), 1068–1076. <https://doi.org/10.1093/jamia/ocw005>.
- Zadvinskis, I.M., Smith, J.G., Yen, P.-Y., 2018. Nurses' experience with health information technology: longitudinal qualitative study. *JMIR.Med. Inf.* 6 (2), e38.
- Zayas-Cabán, T., White, P.J., 2020. The national health information technology human factors and ergonomics agenda. *Appl. Ergon.* 86, 103109.
- Zhang, J., Johnson, T.R., Patel, V.L., Paige, D.L., Kubose, T., 2003. Using usability heuristics to evaluate patient safety of medical devices. *J. Biomed. Inf.* 36 (1–2), 23–30. [https://doi.org/10.1016/S1532-0464\(03\)00060-1](https://doi.org/10.1016/S1532-0464(03)00060-1).