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The influence of electronic health record design on usability and medication safety: systematic review

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Abstract

Background The advantages of electronic health records (EHRs) are well-documented regarding the process of care, enhanced data accessibility and cost savings. However, EHR design can also contribute to usability challenges, with poorly designed EHRs being implicated in user errors including patient overdoses. Our study seeks to evaluate how EHR design influences both usability and medication safety.

Methods A systematic review was conducted of PubMed, EMBASE, CINAHL and the ACM library from 1 January 2009 to 8 October 2024. Eligible studies reported on the impact of specific EHR design elements on usability and/or medication safety, involved healthcare providers and took place in a secondary, tertiary or quaternary care setting. Usability was defined as the extent to which an EHR can be used to achieve specified goals with effectiveness, efficiency and satisfaction, while medication safety related to the risk of drug-related problems, including adverse drug events and medication errors. Design features identified within studies were validated, by cross-referencing these elements with ISO standards regarding design recommendations. A narrative synthesis was conducted, with studies tabulated based on whether they assessed usability and/or medication safety. Patterns were identified and common design elements between studies translated into themes. The Mixed Methods Appraisal Tool was used to evaluate study quality and PRISMA guidelines were followed throughout.

Results Thirty-two studies were identified. The design features described in these studies fit within seven broad design themes: searchability, automation, customisation, data entry, workflow, user guidance and interoperability. EHR systems that prioritised these areas were associated with higher reported usability and enhanced medication safety, while the opposite was found for systems that overlooked these design aspects. Our review also highlighted the numerous ways these themes can be implemented, while identifying the contributing factors that enable their successful implementation.

Conclusion The design of EHRs can enhance or undermine usability and medication safety, depending on the searchability and customisability of these systems, how data entry processes and provider workflow are facilitated and how automation, user guidance and interoperability are implemented. Future EHR evaluations should be performed throughout the design process and consensus building is required regarding what exactly constitutes a design element, within an EHR context.

Keywords Electronic health record, User-centered design, Attitude of health personnel, Medication safety, Usability

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Background

Electronic health records (EHRs) are real-time patient-centred records, maintained by a patient's healthcare providers (HCPs), encompassing both clinical and administrative data [1, 2]. EHRs have also been defined by the Council of the European Union as a "collection of electronic health data related to a natural person collected and processed for the purpose of the provision of healthcare". The advantages of EHRs are well-documented about the process of care, enhanced data accessibility and cost savings [3, 4]. However, EHRs are not without their challenges.

While rates of EHR implementation are steadily increasing on a global scale, the usability of many of these systems remains inadequate [5–7], causing inefficiencies associated with provider burnout [8]. Non-intuitive EHR interfaces are a longstanding complaint among clinicians, with user feedback repeatedly citing their negative impact on the work environment of health care staff [9]. These poorly designed systems can have serious ramifications for the public, with numerous case studies linking patient overdoses to flaws in EHR human-system interface design [10, 11]. Indeed, information overload, resulting from poor data display and excessive alerting, has repeatedly been linked with not only a higher cognitive load for physicians, but also increased error rates [12].

It is widely understood that these unintended safety risks, resulting from EHR use, can only be addressed through effective interface and system design and, in an effort to address these usability and design issues, guidance from other industries has often been utilised [13, 14]. Zahabi and Kaber, for example, categorised EHR usability problems using principles derived from the design of human–computer interfaces in industry and academia [15, 16]. Pruitt et al. used visual display guidelines from the automotive, aviation and nuclear industries to inform their EHR design recommendations [17]. ISO 9241, a multi-part standard from the International Organization for Standardization (ISO) on usability and ergonomics for products and services in technology, has also been employed by numerous review studies, to establish usability evaluation goals and inform EHR and CPOE design recommendations [13, 18–20].

The ISO defines usability as "the extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" [21]. The definition of medication safety varies widely depending on the data source used [22]. In this study, medication safety is related to the risk of drug-related problems [23], including adverse drug events and medication errors, within an EHR context [24].

Existing review studies have examined the impact of specific EHR elements — including interface design, ease of navigation, infobuttons, visualisation dashboards and free-text communication — on usability and safety [25–30]. Currently, there are no published systematic reviews focusing on how EHR design, overall, influences both usability and medication safety. This is concerning, given the growing evidence supporting the link between EHRs with poor usability and increased medication errors [31]. Indeed, a comprehensive review focusing on the impact of EHR design, in particular, on these outcomes, could provide practical insights regarding how usability and medication safety can be promoted in the design process of an EHR and allow health systems can prioritise optimisation efforts. It may also highlight critical gaps in the literature and inconsistencies regarding how studies in this area are conducted and reported.

This narrative synthesis systematic review aimed to (i) identify EHR design elements using ISO standards and (ii) provide a narrative, textual account of how these design features positively or negatively influence usability and/or medication safety.

Methods

Search strategy

The Cochrane Library and PROSPERO were searched for similar reviews/registered protocols to avoid replication. PubMed, Embase, CINAHL and the ACM library were then searched using a combination of keywords and MeSH terms/Major or Minor Subjects/major focuses from 1 January 2009 to 13 December 2023. The initial search strategy was developed in PubMed and adjusted according to the indexing systems of other databases. No filters on the study design were applied. The strategy was then revised appropriately with the assistance of a medical librarian (see supplementary material 1). This search was then updated to include papers published from 13 December 2023 to 8 October 2024. PRISMA 2020 guidelines for reporting were followed throughout this review (see supplementary material 2 for checklist) [32].

Study selection

Studies were included if they (i) reported on the impact of specific EHR design elements on user satisfaction, effectiveness, efficiency and/or medication safety, (ii) used an experimental or observational design, (iii) took place in a secondary, tertiary or quaternary care setting and (iv) involved HCPs. Usability was defined as the extent to which an EHR can be used to achieve specified goals with effectiveness, efficiency and satisfaction, while medication safety related to the risk of drug-related problems, including adverse drug events and medication errors. Studies in the English language were considered.

While articles pertaining to EHRs, electronic medical records (EMRs) and electronic patient records were included, studies examining a personal health record, patient health record or a personal health application were excluded, in line with other review studies [10, 20]. Studies focusing on the design features desired by users, but not the actual features present in their current EHR, were excluded, as were studies involving simulations. Studies describing the process of redesigning an EHR, which contained multiple confounding factors (i.e. other changes were made that were unrelated to EHR design) were excluded.

Search results were imported into EndNote X9 and duplicates were removed. Titles and abstracts were screened against the eligibility criteria by MC and SC. A full-text analysis of the potentially relevant studies followed the title and abstract screening. MC completed the initial full-text analysis, with the same procedures as used for the title and abstract screening being followed.

Data extraction

Following study selection, MC used a standardised data extraction form to collate information on study characteristics, user groups, EHR system, study method, design element(s) evaluated, and user satisfaction, effectiveness, efficiency and/or medication safety-related outcomes.

The design features chosen were validated, by cross-referencing these elements with ISO standards pertaining to design recommendations for interactive systems [33–35], a software's user interface [36], menu dialogues [37], forms [38], and the visual presentation of information [39].

Quality assessment

For this review, the Mixed Methods Appraisal Tool (MMAT) was chosen so as to appraise the quality of studies and to assess their risk of bias [40]. For each study design (qualitative, quantitative RCTs, non-randomised quantitative studies, quantitative descriptive studies, mixed methods studies), there was a quality checklist containing five items. All items were labelled as 'Yes', 'No', or 'Can't tell'. All studies obtained a score of 0 to 5. The MMAT user guide advises that researchers agree on an acceptable dropout rate for the question 'Are there complete outcome data?' (2.3, 3.3). It was decided a priori that a paper would qualify as 'Yes' should a dropout rate of $\leq$30% participants be reported [41, 42]. The quality of all articles was assessed by MC, with over 35% (14/28) of articles corroborated by SC to ensure consistency.

Synthesis of the evidence

To ascertain whether a meta-analysis was suitable, the included studies were considered based on their similarity regarding participants, intervention, comparison and outcomes, in collaboration with a member of the RCSI Data Science Centre [43]. There was substantial heterogeneity, for example, regarding each study's population (participants), how EHR design was assessed (intervention), whether EHR design was being compared to previous iterations (comparison) and what was deemed a positive result (outcomes). Therefore, it was concluded that a meta-analysis was inappropriate for our review and a narrative synthesis was conducted, using the procedures outlined in the European Social Research Council Guidance on the Conduct of Narrative Synthesis in Systematic Reviews [44]. Full details on the narrative synthesis performed can be found in supplementary material 3 [12, 40–42, 45–56].

Studies were tabulated based on whether they assessed usability (in particular, user satisfaction, effectiveness or efficiency) and/or medication safety then grouped based on the ISO recommendations their investigated design features matched to.

Patterns were then distinguished and shared design elements among studies were translated into themes. Papers were then reevaluated from the perspective of each theme. An iterative process was used to refine these themes. The findings were then synthesised so as to obtain a narrative pertaining to our research question.

Results

Overview

The online databases' search identified 3914 publications. After removal of duplicates ($n=346$), 3568 articles remained to be screened via title and abstract. Of these studies, 3408 were excluded. The most frequent reason for exclusion was that only EHR usability was assessed, and not EHR design. Upon full-text review, 128 papers were excluded, leaving 32 studies for inclusion in our review. An overview of the database search and screening process can be found in Fig. 1.

Study characteristics

The main characteristics of the included studies and their findings are summarised in Table 1. These studies were grouped based on whether they assess usability (specifically user satisfaction, efficiency or effectiveness, in line with the ISO definition of usability) and/or medication safety. The design elements identified in our review were validated by matching them to specific ISO recommendations, as seen in the final column of Table 1.

This review includes studies utilising a variety of methods, as described in 4.3. The most common methods used were survey (14 studies) and interview (six studies). A range of study participants were present across studies, from physicians and nurses to social workers and

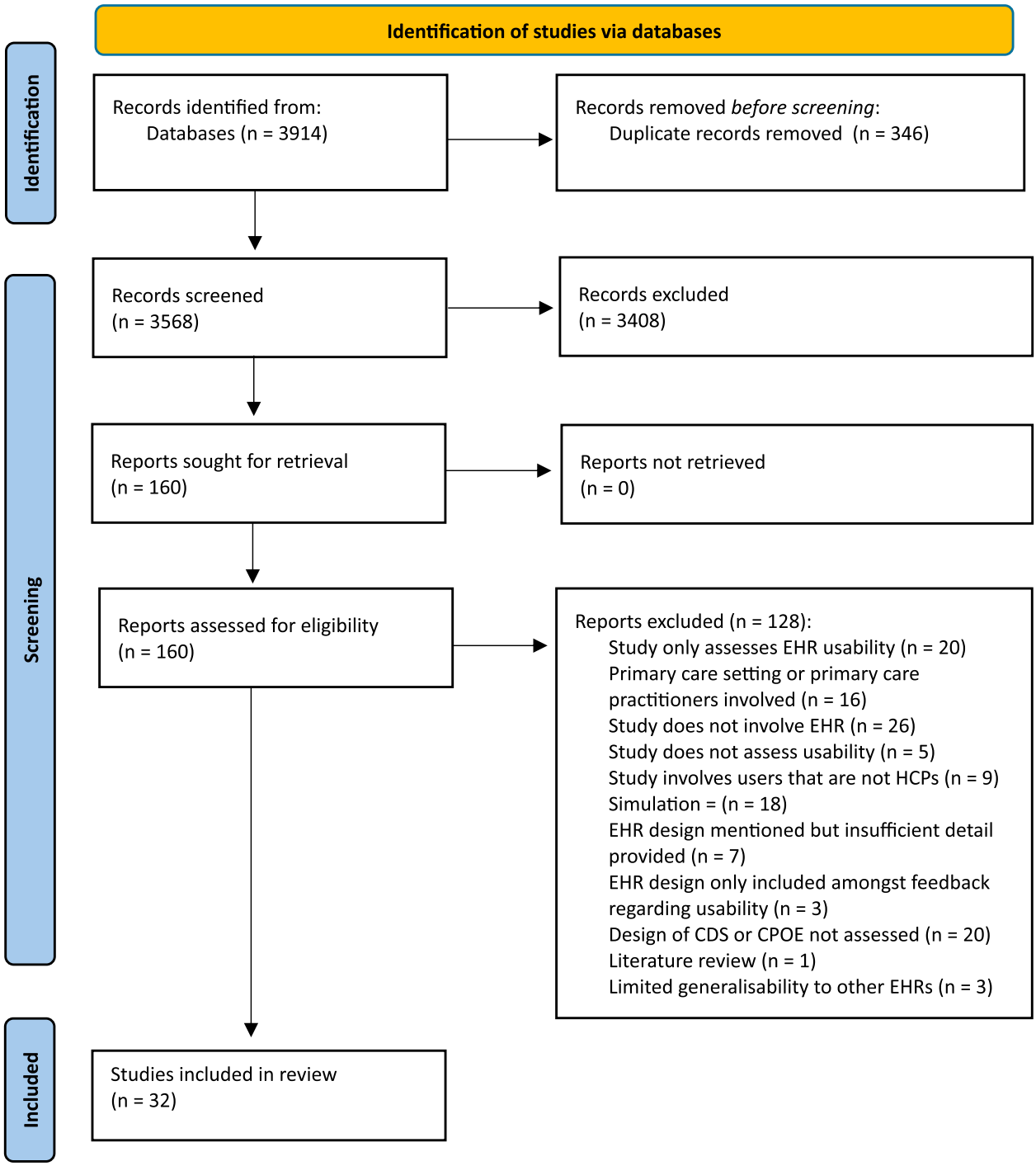

Fig. 1 Systematic review flow diagram

Abbreviations: *CDS* Clinical Decision Support, *CPOE* Computerised Provider Order Entry, *EHR* Electronic Health Record, *HCP* Healthcare Professional

psychologist [59, 63, 64, 68, 69, 74–76, 78, 80, 81, 83, 85, 86, 88].

Twenty-one studies involved assessments of user satisfaction [57–60, 62–66, 76, 78–81, 83, 86–88], 10 studies assessed effectiveness [61, 68–72, 77, 82, 84–88], nine assessed efficiency [76–83, 86], and six studies assessed medication safety [73–75, 84, 85, 87].

Table 1 Summary of the main characteristics of the included studies and their findings. These studies are grouped based on whether they assess usability (specifically user satisfaction, efficiency or effectiveness) and/or medication safety. The positive, negative or mixed findings of these studies are indicated by a '+', '–' or '+/-' symbol in the 'Study Outcome' column. The design elements identified in our review were validated by matching them to specific International Organization for Standardization (ISO) recommendations, as seen in the final column

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
User Satisfaction									
1	Bersani et al., 2020 [57].	Epic EHR	Field observations	Nurses and prescribers	N/A	Design of Patient Safety Dashboard	Describe use of Patient Safety Dashboard and provide insight into tool adoption	- The inability to change alerts was deemed a usability issue. - The dashboard's inability to fit into user workflow was a usability issue.	**7.4.2** Designing…user interface to meet user requirements [34]; **9.5.5** Error messages should be removed… prior to correction, if the user requests removal of the message [36].
2	Khairat et al., 2021 [58].	Epic EHR	Semi-structured interview	Resident, fellow and attending physicians	25	Design of EHR screen	Assess physician perceptions around features of key screens	+ Time-stamp feature to identify new lab results was a positive EHR usability feature. + Presence of search functionality was a favourable feature (72% of participants). - Unclear note authorship was unfavourable. - Unclear lab order status was unfavourable. - Default information presentation that masks clinically relevant details was unfavourable. - Too many clicks was unfavourable. - Too much scrolling was unfavourable. - Poor default filter setting was a negative EHR usability feature. - EHR incapacity for customisation was a negative EHR usability feature. - Vertical layout of information makes it difficult to trend patient data at a glance.	**5.1.4** Search time considerations [37].; **8.2.3** Enable individualisation of the user interface look and feel [35].; **4.4.1** Legibility of characters and symbols [39].; **5.1.2** Required information [39].; **7.4.2** Designing…user interface to meet user requirements [34].
3	Kim and Lee, 2023 [59].	Smartphone-based EMR (mEMR)	5-point Likert questionnaire survey	Nurses	210	Smartphone-based EMR	Establish the usefulness and ease of use of using mEMR and preference for using the mEMR	+ The overall mean of perceived usefulness was 3.90 points (SD = 0.97) and ease of use of the smart-phone based EHR was 3.94 points (SD = 9.82). + Users wanted to continuously use the mEMR (mean = 4.04, SD = 1.09) and to recommend the mEMR to others (mean = 4.24, SD = 0.96).	**5.3.4.3** The interactive system should present information appropriately on different device types [33].

Table 1 (continued)

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
4	Mishra et al., 2022 [60].	EHR (Cerner, Epic)	Questionnaire survey (open-ended questions and 5-point Likert scale questionnaire)	Physicians, residents/fellows, nurses, advanced practice providers, allied HCPs	816	Design of EHR	Identify the features that impact EHR experience	+ Satisfaction with vendor EHR design quality was low (29%). + Order sets were found useful by 32% of respondents in one institution, and by 30% in another. + Clinical templates were found useful by 58% of respondents in one institution and 62% in another. - Fewer click boxes were desired by respondents.	**8.4.2** Optimize the number of steps required for any task [35].; **7.4.2** Designing…user interface to meet user requirements [34].
5	Nasrallah et al., 2024 [61].	EHR	Focus group	Clinicians	13	Design of PRO dashboard	Determine clinician perceptions towards design of PRO dashboard	+ Clinicians were enthusiastic about dashboard and had a positive preference for its features. +/– Visualising RA outcome trajectories in a graphical format was useful, however some users wanted higher values on the graph to be oriented higher up on the page.	**8.2.3** Enable individualisation of the user interface look and feel [35].; **5.2.2.1.** The interactive system should provide information that guides the user [33].
6	Nolan et al., 2017 [62].	EMR and commercial EHRs (customised versions of General Electric Company Centricity and Cerner PowerChart)	Questionnaire survey (categorical and open-ended questions and 5-point Likert scale questionnaire)	ICU attendings, fellows, advanced practice providers, rotating residents	156	EMR/EHR data display	Identify users' data display preferences when admitting new patients	- Application "tabs" result in too many clicks (not desired by users). +/– 64% of respondents prefer a computer system that intelligently 'hides' low-yield data. 23% of respondents would not trust the 'hiding' rules, which may suppress important data. + Robust search features was a desirable key theme that arose. + "Flagging" of abnormal data preferred. + 63% of clinicians prefer the use of clinical abbreviations. + Abbreviated text descriptors (instead of verbose text-based descriptors) preferred by 57% of respondents. + Color-coding preferred by 60% of respondents. + "Limited group" of metadata preferred by 59% of clinicians.	**5.1.4** Density of displayed information [39].; **5.1.4** Search time considerations [37]. **4.4.1** Legibility of characters and symbols [39].; **7.4.2** Designing…user interface to meet user requirements [34].; **8.4.7** Colour assignment to categories of information [39].
7	Ries et al., 2012 [63].	Siemens Soarian Clinicals EMR	5-point Likert questionnaire survey (QUIS)	Clinicians	11	Summarised patient history	Evaluate usability of summarised oncology history (via cancer diary)	+ Overall user satisfaction with the presence of a summarised oncology history was highly positive (median = 4.38).	**5.6.2.2** The interactive system should allow the user to select data (using recognition) rather than having to manually input data (using recall) [33].

Table 1 (continued)

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
8	Sidebottom et al., 2012 [64].	Excellian EHR (Allina's EHR product developed by Epic Systems Corporation)	Focus groups	Nurses	50	Alerts	Examine attitudes and reactions to alerts in the inpatient setting	- Bright colours were pleasing to users. +/– Reasons for not using banners included preference for other sources of information and information overload, but users liked that they were only one click away and not "in their face". - More consistent colours and categories for orders were desired by users. - Overly "wordy" alert sections was amongst negative user feedback. + The format of dashboards was overwhelmingly preferred to alert sections. +/– Dashboards that fit into workflow were perceived positively, but actual actions required were sometimes unclear. - Intrusive and non-selective use of pop-up alerts was disliked.	**5.1.1** Information location [39].; **5.1.4** Density of displayed information [39].; **8.4.7** Colour assignment to categories of information [39].; **7.2.1** Every input… should produce timely and perceptible feedback from the system [36]. **9.5.3** Error messages should convey what is wrong, what corrective actions can be taken, and the cause of the error [36].
9	Thayer et al., 2021 [65].	Commercial EHR (Epic systems)	5-point Likert questionnaire survey	Attendings, fellows, advanced practice nurses, nurses	50	Interactive information visualisation	Assess functionality and user satisfaction regarding interactive information visualisation (Asthma Application Timeline)	+ Users were satisfied with the interactive information visualisation (mean = 4.4, SD = 0.9) and preferred it over the standard EHR alone (mean = 4.0, SD = 1.4).	**5.6.2.2** The interactive system should allow the user to select data (using recognition) rather than having to manually input data (using recall) [33].

Table 1 (continued)

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
10	Wawrzyniak et al., 2019 [66].	EHR	Interview	Laboratory pharmacists, clinical pharmacists, anaesthetists, radiologists, infectious disease specialists, cardiologists, emergency physicians, neurologists	9	Design of EHR	Establish EHRs' usability failures and potential impacts	- Scattered data across EHR, other software and paper records considered a usability weakness by 7/9 respondents. - Difficult-to-access lab results included as a usability weakness by 5/9 respondents. - Lack of information on already ordered radiological exams and blood tests cited as a usability weakness by 4/9 respondents. - Fixed scale for diagrams was a usability weakness for 4/9 respondents. - Too many tabs cited as a usability weakness by 7/9 respondents. - Presence of irrelevant alerts was a usability weakness for 4/9 respondents. - Data entered not being automatically saved deemed a usability weakness by 5/9 respondents. - Lack of interface customisation considered a usability weakness by 4/9 respondents.	**5.1.1** Information location [39].; **5.6.2.4** The interactive system should ensure that the users do not lose their work as the result of use errors or system errors [33].; **8.2.3** Enable individualisation of the user interface look and feel [35].; **5.1.2** Required information [39].; **9.4.4** Rows of tabs [38].; **5.2.2** If system-initiated user guidance messages are no longer applicable…the information should be removed [36].
Effectiveness									
11	Black et al., 2024 [67].	EHR	Pre-post interventional study	Nurses	14650 (eligible patients); 13150 (alerts fired)	Soft stop alert	Evaluate the impact of a soft stop alert to increase the number of clinically indicated COVID-19 vaccinations	+ Vaccine ordering rates increased from 4.0 to 13.0% at the academic hospital (OR 4.01, 95% CI, 3.39 – 4.74, $p < 0.001$) and from 7.4 to 11.6% at the community hospital (OR 1.62, 95% CI 1.23 – 2.13, $p < 0.001$) after alert implementation. +/– Administration increased post-alert from 3.6 to 12.7% at an academic hospital (OR 3.21, 95% CI 2.70 – 3.82, $p < 0.001$) but was unchanged at a community hospital, 6.7 to 6.7% (OR 0.99, 95% CI 0.73 – 1.37, $p = 0.994$).	**7.2.1** Every input… should produce timely and perceptible feedback from the system [36].

Table 1 (continued)

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
12	Collier et al., 2009 [68].	EMR	Prospective cohort study	Attending rheumatologists, rheumatology fellows	15	EMR-integrated calculator	Assess physicians' concordance with Disease Activity Score in 28 joints (DAS28) categories calculated by an EMR–embedded disease activity calculator	+ The categorised DAS28-calculated results concurred most with physician-predicted DAS28 categories in patients with predicted remission (120 of 160 patient visits, 75% accuracy) or with high disease activity (41 of 61 patient visits, 68% accuracy). - Categorised DAS28-calculated results and physician-predicted DAS28 categories concurred least in patients with moderate (50 of 104 patient visits, 48% accuracy) or low disease activity (34 of 55 patient visits, 62% accuracy).	**5.2.2.1**. The interactive system should provide information that guides the user [33].
13	Dekarske et al., 2015 [69].	CPOE (Sunrise Clinical Manager) linked to a homegrown EHR	Prospective randomised crossover study	Clinicians	22	Medication override options	Examine the effect of customising medication alert override options on the appropriateness of override selection related to patient allergies, drug dosing, and drug–drug interactions when ordering medications	+ Customised medication alert override option had an overall higher rate of appropriateness when compared to the non-customised configuration.	**9.5.5** Error messages should be removed… prior to correction, if the user requests removal of the message [36].
14	Morgan et al., 2022 [70].	CDS within an Epic EHR	Cluster-RCT	Resident physicians, advanced practice providers	70	CDS hooks	Determine if contextually relevant CDS Hooks prompts can increase utilisation of a SMART on FHIR medical reference app (MDCalc)	+ Providers in the intervention group (who received a collection of CDS Hooks prompts suggesting the use of 6 medical calculators in MDCalc) used the MDCalc for EHR app to view a study calculator in 6.0% of the unique interactions compared to 2.6% in the control group (OR 2.45, 95% CI 1.15 – 5.22, $p = 0.02$); an increase of 130%. + App usage was significantly greater for the intervention group providers for 2 of the 6 calculators. + The percentage of providers who viewed at least 1 study calculator in the app during a unique interaction increased from 37.1% in the control group to 80% in the intervention group ($p < 0.001$).	**5.2.2.1**. The interactive system should provide information that guides the user [33].

Table 1 (continued)

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
15	Pierce et al., 2020 [71].	Cerner EHR	Interrupted time series analysis	Hospital staff members	N/A	Design of UI	Determine the impact of UI redesign on evidence-based clinical quality metrics (i.e. screening for fall risk, depression, alcohol and drug misuse, and advance directive planning)	+ Conditionally enabled options for deferral reasons contributed to overall improvement in screening rates (baseline screening rate for the provision of advance directive information increased an average of 0.44% [95% CI 0.10 - 0.79] per month, $p = 0.017$; depression screening increased by 2.97% [95% CI 2.50 - 3.44] per month, $p < 0.0001$; screening for risk of fall improved 3.52% [95% CI 2.92 - 4.11] per month, $p < 0.0001$; alcohol/drug screening improved by 3.07% [95% CI 2.71 - 3.43], $p < 0.0001$). + Consistent and clear labels contributed to overall improvement in screening rates. + Date of prior screening (in read-only format) contributed to overall improvement in screening rates. + Auto-populating date field contributed to overall improvement in screening rates. + Modified modal dialogues contributed to overall improvement in screening rates.	**5.1.1** Information location [39].; **6.8.1** Field default values [38].; **6.3.1** Entry field format [39].; **6.5.5** Disabled areas [38].; **7.2.1** Every input… should produce timely and perceptible feedback from the system [36].
16	Salmasian et al., 2020 [72].	Epic EHR	Quasi-experimental study with a historical cohort design	Practitioners	2,558,746 (orders placed)	Patient photographs	Evaluate whether the use of non-interruptive display of patient photographs in an EHR banner is associated with a decreased rate of WPOE errors	+ The risk of WPOE errors was significantly lower when the patient's photograph was displayed in the EHR (OR 0.72; 95% CI 0.57 - 0.89).	**5.1.1** Information location [39].

Table 1 (continued)

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
Medication Safety									
17	Gildon et al., 2019 [73].	Success EHS, CentricityTM EMR and Epic	Cross-sectional, descriptive study	Prescribers	1518 (number of prescriptions reviewed for Clinics 1, 2, and 3, respectively, were 477, 408, and 633)	Design of EHR	Identify e-prescribing errors that could have been avoided if EHRs had met requirements set by the American Academy of Pediatrics	- Tall-man lettering reduces medication selection errors but was not present across clinics. - Medication-specific indications are a requirement for safe and effective e-prescribing, but were not present across clinics. - Pediatric-specific adverse-effect warnings are a requirement for safe and effective e-prescribing and they were not present across clinics. - Information regarding alternative therapies is a requirement for safe and effective e-prescribing, but was not present across clinics. - Automatic strength to volume conversion for liquid medications is a requirement for safe and effective e-prescribing, but was present in one clinic, partially present in another clinic and absent in another. + A dose range check was present in 1 clinic and partially present in the remaining 2 clinics and is a requirement for safe and effective e-prescribing. + Patient information — the patient's date of birth, weight in kg, height in cm and history of adverse effects — should be present within EHR for safe and effective e-prescribing and this requirement was met/partially met across clinics. - Medication information — indication-based dosing, individual and daily dose alerts, weight-based dosing calculation, all available formulations — should be present within EHR for safe and effectivee-prescribing. Certain elements pertaining to medication information were present or partially present across clinics (e.g. weight-based dosing calculations), but many element were absent (e.g. common formulations requiring extemporaneous compounding or combinations of active ingredients).	**4.4.1** Legibility of characters and symbols [39].; **6.8.1** Field default values [38].; **6.6.1** Information needed [38].; **9.5.3** Error messages should convey what is wrong, what corrective actions can be taken, and the cause of the error [36].

Table 1 (continued)

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
18	Ratwani et al., 2018 [74].	Epic and Cerner EHRs	Retrospective analysis	Clinicians	9,000 (patient safety reports)	Design of EHR	Understand specific usability issues and medication errors in the care of children, patient safety reports were analysed that were likely related to EHR use	- Hard to find or confusing information display was a contributing factor in 36.7% of safety events resulting from system feedback errors. - Confusing data entry locations was a contributing factor in 6.2% of safety events resulting from data entry. - Difficult-to-interpret alerts was a contributing factor in 3.5% of safety events resulting from visual display errors. - Automation or conversion with no clear feedback was a contributing factor in 2.4% of safety events resulting from system feedback errors.	**5.1.1** Information location [39].; **5.6.3.2** When the interactive system is able to correct errors automatically, it should inform the user of the execution of the corrections [33]. **9.5.3** Error messages should convey what is wrong, what corrective actions can be taken, and the cause of the error [36].
19	Turchin et al., 2014 [75].	EHR	Retrospective analysis	Clinicians	960,000 (electronic prescriptions)	Design of EHR UI	Determine effect of EHR UI changes on internal prescription discrepancies	+ Adding "as directed" option to a frequency drop-down resulting from system feedback errors. + A non-interruptive alert decreased prescription discrepancies by 145/month ($p = 0.03$). - Adding a "Renew / Sign" button to the Medication module did not affect prescription discrepancies.	**5.1.4** Search time considerations [37]. **9.2.2** Limited choice options[38].; **7.2.1** Every input… should produce timely and perceptible feedback from the system [36].;
User Satisfaction and Efficiency									
20	Duhm et al., 2016 [76].	EMR	Questionnaire survey (categorical and open-ended questions and 5-point Likert scale questionnaire)	Physicians	14	Mobile tablet-based EMR	Examine physicians' perception of mobile tablet	*User satisfaction* + Mobile EHR associated with high degrees of user satisfaction and motivation to use tablets (mean = 2.21, 95% CI 1.86 - 2.64). *Efficiency* + Mobile EHR saved time spent on data retrieval (by 9.6 minutes) and time spent during preparing (4.8 minutes), conducting (6.5 minutes) and postprocessing (0.8 minutes) ward rounds, according to users.	**5.3.4.3** The interactive system should present information appropriately on different device types [33].

Table 1 (continued)

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
21	Ebbers et al., 2024 [77].	EHR	Time-and-motion study, questionnaire survey	Physicians	196 (consultations recorded); 26 (questionnaires completed)	Design of EHR-embedded care pathway with structured data recording	Determine the effect of EHR-embedded care pathway with structured data recording on burden of physicians	*User satisfaction* + The introduction of a structured documentation template, smart phrases and content importing technology, standardised order sets and the automatic capture of relevant data significantly increased perceived usefulness (from a mean factor score of 3.08 to 3.63) and ease of use (from a mean factor score of 2.77 to 3.45) of the EHR. *Efficiency* + Implementing an EHR-embedded care pathway with structured data recording for initial oncology consultations was associated with a 3.69 min reduction in time spent on the EHR ($p = 0.003$), a 27 % decrease. - For follow-up consultations, there was no significant effect on total EHR time, with the analysis showing a 0.53 min difference (13 %) ($p = 0.219$).	**8.4.2** Optimize the number of steps required for any task [35].
22	Exeni McAmis et al., 2021 [78].	EHR	5-point Likert questionnaire survey	Physicians	818	EHR documentatio-n	Identify physician/practice factors associated with, and physician attitudes towards, different documentation methods	*User satisfaction* - Electronic transcription (ET) was rated less accurate than direct typing (DT) (2.9 vs 3.6; p < 0.001) and human transcription (HT) (2.9 vs 3.1; $p < 0.001$).	**8.4.2** Optimize the number of steps required for any task [35].

Table 1 (continued)

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
								Efficiency - DT was considered less efficient than ET (2.7 vs 3.6; $p < 0.001$), HT (2.7 vs 3.1; $p < 0.001$), and scribe (2.7 vs 3.9; $p < 0.001$). - ET, HT, and scribe did not significantly differ from each other, regarding efficiency.	
23	Lloyd et al., 2023 [79].	EMR	Free-text questionnaire survey (NuHISS)	Doctors, nurses	112	Design of EHR	Describe the perspectives of medical and nursing clinicians on EMR usability	*User satisfaction*	**5.1.1** Information location [39].; **5.1.4** Density of displayed information [39].; **8.2.3** Enable individualisation of the user interface look and feel [35].; **4.4.1** Legibility of characters and symbols [39].; **8.4.2** Optimize the number of steps required for any task [35].; **5.1.2** Required information [39].; **7.4.2** Designing…user interface to meet user requirements [34].; **5.3.4.3** The interactive system should present information appropriately on different device types [33].;

Table 1 (continued)

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
								- Clinicians had a negative impression of hybrid records. - Numerous log-ins and sign-outs challenged users. - Low searchability and difficulty locating information across EHR were perceived negatively by respondents. - Severity of allergy status not displayed deemed a major fault of system. - "Note bloat" (due to copy-paste functionality) was criticised by clinicians. - Font choices deemed "questionable". - System requiring users to change their workflow/practice/processes was amongst negative feedback from clinicians. - A desire for tailoring of EMRs to individual user's requirements (e.g. reduced clicks) was described. - Fixed font sizes criticised for making information difficult to read. + The ability to access patient notes remotely was deemed extremely helpful. *Efficiency* - Hybrid records were deemed slow by clinicians. - Numerous log-ins and sign-outs wasted time. - Inability to use multiple inputs slowed down clinic appointments.	
24	Meidani et al., 2023 [80].	CDS within an EMR	5-point Likert questionnaire survey (SUS), interviews	Anaesthesiology residents, ICU fellow	9	Design of CDSS for arterial blood gas interpretation and ordering	Assess the usability of an electronic medical records-embedded CDSS for arterial blood gas interpretation and ordering	*User satisfaction*	**9.5.5** Error messages should be removed… prior to correction, if the user requests removal of the message [36]. **8.4.2** Optimize the number of steps required for any task [35]. **7.4.2** Designing…user interface to meet user requirements [34].

Table 1 (continued)

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
								- Participants' dissatisfaction with the interface design requiring scrolling for completing different forms contributed to usability scores ranging from 57.5 to 72.5 (mean = 67.22 ± 4.58). + The ability to override alerts and the separation of buttons for arterial blood gas interpretation and diagnosis contributed to the usability scores of participants ranging from 72.5 to 87.5 (mean = 80.00 ± 4.84, $p < 0.001$). *Efficiency* - Long time required to fill out lengthy forms for interpretation or diagnosis, according to respondents.	
25	Pruitt et al., 2021 [81].	EHR (Cerner Corporation, Epic Systems)	Interviews	Emergency physicians	55	Design of EHR	Identify physicians' perceived EHR usability strengths and shortcomings	*User satisfaction*	**5.1.1** Information location [39].; **5.1.4** Density of displayed information [39].; **5.6.2.4** The interactive system should ensure that the users do not lose their work as the result of use errors or system errors [33].; **8.4.2** Optimize the number of steps required for any task [35]. **4.4.1** Legibility of characters and symbols [39].; **7.4.2** Designing…user interface to meet user requirements [34].; **5.1.8** Functional grouping [39].; **7.2.1** Every input… should produce timely and perceptible feedback from the system [36].; **5.2.2.1** The interactive system should provide information that guides the user [33].

Table 1 (continued)

AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
							- Documentation aids were appreciated in 8 comments (of the 28 comments regarding data entry; 28.6%). - Incorrect field auto-population was a concern in 5 comments (of the 9 comments regarding system automation and defaults; 55.6%). - Auto-refresh was a source of frustration in 2 comments (of the 9 comments regarding system automation and defaults; 22.2%). - Excessive number of clicks required to complete the task were complained about in 28 comments (of the 65 comments regarding workflow support; 77.8%). - Inability to enter order without additional information was a source of frustration in 2 comments (of the 65 comments regarding workflow support; 3.1%). - Ability to open multiple patient charts was a source of concern in 2 comments (of the 39 comments regarding visual display; 5.1%). - Inappropriate pop-ups cited in 8 comments (of the 21 comments regarding alerting; 38.1%). - Difficult medication tapering process in electronic orders were described in 5 comments (of the 28 comments regarding data entry; 17.9%). - Lab trend display was considered difficult to look at in 5 comments (of the 39 comments regarding visual display; 12.8%). - Image and lab test results being present in different programs was deemed a usability shortcoming in 9 comments across vendors (of the 11 comments regarding interoperability; 81.9%). + The efficient display of information was deemed a usability strength in 21 comments (of the 39 comments regarding visual display; 53.8%).	

Table 1 (continued)

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
								Efficiency - Quick order's ability to save time was a cross-hospital and cross-vendor usability theme, with 5 comments received from participants (of the 65 comments regarding workflow support; 7.7%).	
26	Robertson et al., 2024 [82].	Cerner EMR	Mixed-methods observational study (semi structured interview and usage logs)	Clinical staff	15 (interviews)	EHR enhancement	Determine use and user perceptions regarding the value of introductng a stroke summary page and data collection form	*User satisfaction* + Stroke summary page limited data input which led to staff perceiving it as unreliable. + Desire for the ability to include free text or a different presentation format in stroke summary page. + Stroke summary page was easy to use. + Stroke summary page eliminated need to navigate through multiple tabs. - Lack of navigation in and out of data collection forms was seen as "annoying". - Challenges with interoperability relating to data collection forms, due to each site having different administrative systems. *Efficiency*	**5.1.1** Information location [39].; **5.1.4** Density of displayed information [39].; **5.1.4** Search time considerations [37].; **8.2.3** Enable individualisation of the user interface look and feel [35].; **7.4.2** Designing…user interface to meet user requirements [34].; **5.6.2.2** The interactive system should allow the user to select data (using recognition) rather than having to manually input data (using recall) [33].

Table 1 (continued)

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
								+ Stroke summary page enhanced efficiency, according to users, due to the transparency and visibility of information. - Data collection forms were deemed inefficient, as they did not fit into workflow (e.g. it was unclear if forms had already been commenced/completed).	
27	Zhang et al., 2019 [83].	Epic EHR	Interviews	Surgeons, oncologists psychologists, social workers, medical assistants	11	Design of PRO system	Determine how well an EHR-integrated PRO system fits clinical workflows and individual needs	*User satisfaction*	**7.4.2** Designing…user interface to meet user requirements [34].; **8.2.3** Enable individualisation of the user interface look and feel [35].; **5.2.2.1** The interactive system should provide information that guides the user [33].
								- Frequency of EHR locking, with only certain users being able to unlock screen, was deemed disruptive. - Physicians desired more visualisation options. +/– PRO considered integral to patient care by psychologists and social workers, with physicians viewing it as valuable. However, MAs did not perceive benefits of system to same extent.	
								Efficiency	
								+/– PRO review deemed time-consuming by physicians. However, receiving PRO notifications allowed social workers to reach out "speedily" to patients.	
Effectiveness and Medication Safety									
29	Simpao et al., 2015 [84].	Epic EHR	Cross-sectional study	Providers (nurse practitioners, physicians), pharmacists	2,391,880 (medication alerts)	Alerts	Evaluate an electronic dashboard of hospital-wide electronic health record medication alerts, having deactivated clinically irrelevant DDI alert rules	*Effectiveness*	**5.2.4** User guidance messages should provide the user with specific information relative to the task context [36].

Table 1 (continued)

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
								+ For pharmacists, median alert rate was reduced from 58.74 alerts/100 orders (IQR 54.98 – 60.48) to 25.11 alerts/100 orders (IQR 23.45 – 26.57). For providers, median alert rate was reduced from 19.73 alerts/100 orders (IQR 18.66 – 20.24) to 15.11 alerts/100 orders (IQR 14.44 – 15.49); $p < 0.001$. + For pharmacists, baseline median override rate prior was reduced from 95.14 overrides/100 alerts (IQR 94.16 – 95.46) to 84.38 overrides/100 alerts (IQR 83.04 – 85.44); $p < 0.001$. For providers, median override rate was reduced from 84.22 overrides/100 alerts (IQR 83.27 – 85.69) to 84.91 overrides/100 alerts (IQR 83.96 – 85.21); $p = 0.16$. *Medication Safety* + The hospital's medication serious safety event (SSE) rate decreased from 0.18 events per 10,000 adjusted patient days to 0.08. No SSEs were reported for the medications associated with the deactivated DDI alert rules.	
30	Wright et al., 2018 [85].	Epic EHR	Pre-post test descriptive study	Clinicians	3277 (clinicians)	Alerts	Describe the effect of conversion from a homegrown EHR (with a highly tailored DDI alerting system) to a commercial EHR (with a more general DDI alerting system), on DDI alert and acceptance rates	*Effectiveness*	**5.2.4** User guidance messages should provide the user with specific information relative to the task context [36].

Table 1 (continued)

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
								- Interruptive DDI alert burden increased by a factor of 6 from the legacy EHR to the commercial EHR. *Medication Safety* - Acceptance rate for the most severe alerts fell from 100 to 8.4%, and from 29.3 to 7.5% for medium severity alerts ($p < 0.001$). After disabling the least severe alerts, total DDI alert burden fell by 50.5%, and acceptance of Tier 1 alerts rose from 9.1 to 12.7% ($p < 0.01$).	
User Satisfaction, Efficiency and Effectiveness									
31	Kawamoto et al., 2019 [86].	Epic EHR	Mixed-methods quality improvement study (app use estimation via app logs; health care use measures and guideline compliance retrospective comparison; experimental task-timing study, 5-point Likert scale questionnaire [SUS])	Clinicians	20,516 (times application was used); 12 (physicians in time-savings evaluation); 109 (users completed survey)	Add-on app	Compare health care use measures and guideline compliance and estimate time savings before and after EHR add-on app implementation; measure clinician-perceived usability of app	*User Satisfaction* + Surveys indicated excellent usability (SUS score = 83.90; 95% CI 81.49 - 86.31).	**5.6.2.2** The interactive system should allow the user to select data (using recognition) rather than having to manually input data (using recall) [33].

Table 1 (continued)

	AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
								Effectiveness + Health care use rates remained stable, while orders for clinically appropriate phototherapy during hospitalisation increased for newborns with bilirubin levels above the guideline-recommended threshold (OR 1.84; 95% CI 1.16 - 2.90; $p = 0.009$). *Efficiency* + Add-on apps saved a mean of 66 seconds for bilirubin management tasks compared with commonly used tool 95% CI 53 - 79 seconds; $p < 0.001$).	
User Satisfaction, Effectiveness and Medication Safety									
32	Joseph et al., 2020 [87].	EMR	Pre-post observational study, 7-point Likert scale questionnaire	ICU pharmacists	8 (pharmacists completed survey)	Smart pump	Observe whether there were changes in the frequency of eMAR documentation of dose titrations in epinephrine and norepinephrine infusions (post-smart infusion pump and EMR interoperability); examine whether smart pump/EMR interoperability had any impact on the rate of alerts triggered by the dose-error reduction software; estimate pharmacist satisfaction	*User satisfaction*	**5.6.2.2** The interactive system should allow the user to select data (using recognition) rather than having to manually input data (using recall) [33].

Table 1 (continued)

AUTHOR, YEAR	EHR SYSTEM	STUDY METHOD	POPULATION	SAMPLE	DESIGN FEATURE ASSESSED	STUDY AIM	STUDY OUTCOME	MAPS TO ISO RECOMMENDATION
							+ 87.5% users agreed or strongly agreed that they viewed more accurate and more useful infusion-related data in the EMR after implementation of smart infusion pump/EMR interoperability; with 75% of users agreeing that the interoperability provided incremental value for providing patient care. *Effectiveness* + Documented rate changes increased by 74.9% per administration. *Medication Safety* + Alert firing rate was slightly reduced (by 0.32%).	

Abbreviations: CDS Clinical Decision Support, *CI* Confidence Interval, *CPOE* Computerised Provider Order Entry, *DAS28* Disease Activity Score in 28 joints, *DDI* Drug-Drug Interaction, *EHR* Electronic Health Record, *eMAR* Electronic Medication Administration Record, *EMR* Electronic Medical Record, *HCP* Healthcare Professional, *ICU* Intensive Care Unit, *ISO* International Organization for Standardization, *IQR* Interquartile Range, *NuHISS* National Usability-Focused HIS Scale, *QUIS* Questionnaire for User Interaction Satisfaction, *SSE* Serious Safety Event, *SMART on FHIR* Substitutable Medical Applications, Reusable Technologies on Fast Healthcare Interoperability Resources, *SUS* System Usability Scale, *UI* User Interface, *WPOE* Wrong Patient Order Entry

Overall EHR design was assessed in six studies [60, 66, 73, 74, 79, 81], design of EHR screen/user interface were assessed in three studies [58, 71, 75], alerts were assessed in four studies [64, 84, 85, 88], two studies looked at information display [62, 65], with the remaining papers evaluating more specific design features, such as smartphone-based EHRs and smart pumps [59, 87].

Eighteen studies involved commercial EHRs (including Cerner, Epic, Siemens etc.) [57, 58, 60, 62–65, 70–74, 81–86], two studies involved homegrown EHR systems [69, 75], and 12 studies did not specify the brand of EHR [59, 61, 66–68, 76–80, 87, 88].

Themes

The design features identified fell within the following themes: searchability, automation, customisation, data entry, workflow, user guidance and interoperability. Supplementary material 4 provides a summary of how the included studies fit within each theme, grouped based on the ISO recommendations they correspond to. Each of these themes are discussed below in the context of usability and medication safety.

Searchability

Searchability underpins ISO recommendations *5.1.1*, *5.1.4* and *5.1.4,* which recognise "information location", the "density of displayed information" and "search time considerations" as design features that influence human-system interactions [37, 39].

Systems that are designed to promote searchability are associated with more satisfied users [62, 64, 66, 79, 81–83]. The presence of a search functionality was deemed a favourable feature for 72% of physicians interviewed by Khairat et al., while a questionnaire survey, conducted by Nolan et al., found that robust search features were desirable for users [62]. Meanwhile, EHRs that contain "scattered data" were criticised by participants in two interview studies and one survey study [66, 79, 81]. Lloyd et al. found that hybrid records (where patient data is "scattered" across both paper and electronic charts) were deemed "slow" [79].

Consistency is a critical component of a system that supports searchability. While the desire for consistency, regarding categories for orders, was emphasised by nurses involved in a focus group study conducted by Sidebottom et al. [64], an interrupted time series analysis conducted by Pierce et al. demonstrated that consistency in EHR labels can have a positive impact on screening rates (e.g. baseline screening for risk of fall improved 3.52% [95% CI 2.92, 4.11] per month, $p < 0.0001$) [71].

Efficiently presented information enables users to identify desired information within the EHR [82], while densely presented data is perceived negatively by users [62, 64, 79, 81]. Nolan et al. found that a "limited group" of metadata was preferred by 59% of clinicians and that 64% of respondents prefer a computer system that intelligently "hides" low-yield data [62].

How well an EHR supports searchability can also have serious ramifications for medication safety. Ratwani et al., reviewed 9,000 patient safety reports from three different children's hospitals and identified hard to find or confusing information display as a contributing factor in 36.7% of safety events resulting from system feedback errors [74]. Confusing data entry locations were also a contributing factor in 6.2% of safety events resulting from data entry [74].

Automation

Automation describes the application of technology to achieve outcomes with minimal human input [89]. This corresponds to multiple ISO recommendations, including 5.6.2.4 ("the interactive system should ensure that users do not lose their work as the result of use errors or system errors") and 5.6.3.2 ("when the interactive system is able to correct errors automatically, it should inform the user of the execution of the corrections") [33].

The negative implications of malfunctioning automation, on user satisfaction, emerged from our review [66, 81], and were particularly apparent in an interview study conducted by Pruitt et al. [81]. Here, incorrect field auto-population was a concern in five comments (of the nine comments regarding system automation and defaults; 55.6%) and auto-refresh was a source of frustration in two comments (of the nine comments regarding system automation and defaults; 22.2%. A similar interview study conducted by Wawrzyniak et al. reported that data entered not being automatically saved was deemed a usability weakness by 5/9 respondents [66].

Automation or conversion with no clear feedback was a contributing factor in 2.4% of safety events resulting from system feedback errors, according to Ratwani et al [74]. A 2019 cross-sectional descriptive study conducted by Gildon et al., which examined 1518 prescriptions across three different clinics, also found that automatic strength to volume conversion for liquid medications was not present in one clinic, partially present in another clinic and absent in another, in spite of being a requirement for safe and effective e-prescribing [73].

Customisation

ISO recommendations 8.2.3 and 5.2.4 correspond to the theme of customisation, by advising system designers to "enable individualisation of the user interface look and feel" and stating that "user guidance messages should provide the user with specific information relative to the task context" [35, 36].

EHRs that did not enable customisation were perceived negatively by participants involved in studies conducted by Khairat et al., Lloyd et al., Wawrynziak et al., Zhang et al. and Robertson et al. [58, 66, 79, 82, 83]. Meanwhile, systems where customisation was present appeared more effective, with two different studies reporting that customising medication alerts was associated with a reduced alert burden [84, 85]. Dekarske et al. also conducted a prospective, randomised, crossover study involving 22 clinicians and found that customised medication alert override options had an overall higher rate of appropriateness when compared to the non-customised configuration [69].

Customised medication alerts can enhance medication safety. Simpao et al. found that their hospital's medication serious safety event rate decreased from 0.18 events per 10,000 adjusted patient days to 0.08, as a result of introducing customised medication alerts [84]. Wright et al. reported that the acceptance rate for the most severe alerts (i.e. Tier 1) was higher when their hospital possessed a highly tailored drug-drug interaction alerting system (100%) when compared to a more general one (8.4%), as was the case for medium severity interactions (i.e. Tier 2; from 29.3 to 7.5%) [85].

Data entry

Data entry processes and how EHRs support/hinder it, was a recurrent theme in the studies we included. Numerous ISO recommendations reflect this theme, including 4.4.1 ("legibility of characters and symbols") and 8.4.2 ("optimize the number of steps required for any task") [35, 39].

The choice of data entry modes within an EHR can influence user satisfaction, efficiency and effectiveness [71, 78, 79]. Exeni McAmis surveyed 818 physicians regarding documentation practices, and found that electronic transcription (ET) was rated less accurate than direct typing (DT) (2.9 vs 3.6; $p < 0.001$) and human transcription (HT) (3.1; $p < 0.001$), while DT was considered less efficient than ET (2.7 vs 3.6; $p < 0.001$), HT (3.1; $p < 0.001$), and scribe (3.9; $p < 0.001$) [78]. Meanwhile, a 2024 before-and-after study found that introducing EHR-embedded care pathway with structured data recording significantly increased an EHR's perceived usefulness (from a mean factor score of 3.08 to 3.63) and ease of use (from a mean factor score of 2.77 to 3.45) [77]. However, this intervention only increased efficiency for initial consultations (reducing time spent on EHR by 27%; $p = 0.003$) and not follow-up consultations.

User's opinions of documentation aids vary with the documentation aid in question [81], with a 2022 survey study across two institutions, finding that order sets were only deemed useful by 32% of respondents in one institution, while clinical templates were found useful by 62% of respondents [60].

The impact of data entry modes on medication safety was highlighted by a 2014 retrospective analysis of electronic prescriptions, which found that adding "as directed " option to a frequency drop-down, instead of requiring users to manually enter this information in the < Special Instructions > field, decreased prescription discrepancies by 195/month ($p = 0.0004$) [75].

Workflow

User workflow is a critical component of EHR design, with this theme repeatedly arising in the studies we included. Workflow underpins ISO recommendations 7.4.2 ("designing…user interface to meet user requirements), 6.6.1 ("information needed") and 5.1.2 ("required information") [34, 38, 39].

EHRs that result in excessive clicks and too much scrolling were repeatedly linked with user dissatisfaction [58, 60, 62, 80, 81]. Similarly, numerous log-ins can disrupt user workflows, and present a challenge to clinicians, according to Lloyd et al., while also "wasting" their "time" [79]. In contrast, the presence of quick orders were found to save time across hospitals and EHR vendors, according to Pruitt et al. [81]. Other obstructions to clinician workflow include the severity of patients' allergy status not being displayed [79], difficult medication tapering processes [81], unclear lab order statuses and the absence of information on already ordered radiological exams/blood tests — each of which appeared as sources of user dissatisfaction in our review [58, 66].

The ability to access patient data remotely can facilitate provider workflow [79], with survey recipients in studies conducted by Duhm et al. and Kim and Lee reporting high levels of user satisfaction associated with using mobile or smartphone-based EHRs [59, 76]. Duhm et al. also reported time savings of 9.6 min for data retrieval and 6.5 min for conducting ward rounds, when a mobile EHR was implemented [76].

The absence of information required by users, to complete routine tasks, presented a medication safety risk, in a study conducted by Gildon et al. [38]. Here, medication-specific indications and information regarding alternative therapies were identified as requirements for safe and effective e-prescribing, but were not found to be present across the clinics they assessed.

User guidance

ISO recommendations 7.2.1 and 5.2.2 emphasise the importance of user guidance, by advising that "if system-initiated user guidance messages are no longer applicable…the information should be removed" and that "every

input…should produce timely and perceptible feedback from the system" [36].

How and when EHR systems utilised user guidance had clear implications for user satisfaction. Pop-up alerts, when used intrusively and inappropriately, were criticised by clinicians in two studies [64, 81], while respondents to a 5-point Likert survey distributed by Scheepers-Hoeks et al. reported an average satisfaction score of 3.7 when asked about pop-up alerts more generally [88]. Interestingly, this same study also reported that the average compliance percentage of pop-up alerts (41%, $p < 0.0001$) was significantly higher than that of the physician alert list and EHR section alert methods.

The inability to alter user guidance messages repeatedly presented a challenge for users [57, 66, 80]. Indeed, field observations obtained by Bersani et al. highlighted the inability to change alerts as a usability issue for HCPs [57], while Meidani et al. found that enabling users to override alerts resulted in usability scores of participants ranging from 72.5 to 87.5 (mean = 80.00 ± 4.84, $p < 0.001$) [80].

The impact of user guidance on medication safety can depend on the nature of user guidance chosen, with Turchin et al. reporting that at a non-interruptive alert decreased prescription discrepancies by 145/month ($p = 0.03$) [75]. Meanwhile, Ratwani et al. found that difficult-to-interpret alerts contributed to 3.5% of safety events resulting from visual display errors [74].

Interoperability

ISO recommendations 5.6.2.2 and 5.2.2.1. advise that "the interactive system should allow the user to select data (using recognition) rather than having to manually input data (using recall)" and that "the interactive system should provide information that guides the user", each of which are made possible through systems that can exchange and make use of information (either contained within the EHR, or obtained from connected devices) [33]. A 2012 and 2021 study assessed an EHR application that can pull specific disease-related data (regarding asthma and cancer) from an EHR, and both studies reported high levels of user satisfaction [63, 65].

Morgan et al. assessed the effectiveness of CDS hooks prompts (which retrieve data from the EHR when the provider clicks on a patient chart, and suggests the use of 6 medical calculators in MDCalc where appropriate), in a cluster-RCT, and found that providers in the intervention group used the MDCalc for EHR app to view a study calculator in 6.0% of the unique interactions compared to 2.6% in the control group (OR 2.45; 95% CI 1.15 – 5.22; $p = 0.02$); an increase of 130% [70]. A bilirubin add-on app (which pulled bilirubin-related data from the EHR when providers clicked on it) was associated with excellent usability, improved the number of orders for clinically appropriate phototherapy (OR 1.84; 95% CI 1.16 – 2.90; $p = 0.009$) and saved a mean of 66 s for bilirubin management tasks (95% CI 53 – 79 s; $p < 0.001$) [86].

While EHRs that are designed to make use of pertinent information contained within the EHR may be linked to satisfied users and efficient and effective systems [63, 65, 68, 70, 86], patient factors can also have a bearing on these outcomes. Collier et al. found that the scores obtained from an EHR-embedded rheumatic disease activity calculator did not concur with the scores calculated by physicians, for patients with moderate (50 of 104 patient visits; 48% accuracy) or low disease activity (34 of 55 patient visits; 62% accuracy) [68].

75% of intensive care unit pharmacists agreed that smart infusion pump/EHR interoperability provided incremental value for providing patient care, in a pre-post observational study conducted by Joseph et al. [87]. This same study reported that documented rate changes increased by 74.9% per administration, after introduction of this design feature, while the firing rate of alerts (triggered by the dose-error reduction software) was reduced by 0.32%.

Study quality

We assessed methodological quality and risk of bias using the MMAT (see Table 2).

Two of the eight qualitative studies scored 5/5 on the MMAT, while six scored 4/5 [58, 61, 64, 66, 76, 79, 81, 83]. Of the quantitative RCTs, two studies scored 4/5 [69, 70], and one study scored 2/5 [88]. Six of the quantitative non-randomised studies scored 5/5 [67, 71, 72, 75, 84, 85], and three studies scored 4/5 [68, 77, 87]. Of the quantitative descriptive studies, one study scored 5/5 [73], four scored 4/5 [59, 62, 63, 74], and one study scored 2/5 [80]. All five of the mixed methods studies scored 4/5 [57, 60, 65, 78, 82, 86].

Discussion

This systematic review and narrative synthesis was conducted to explore the literature regarding how EHR design influences usability and medication safety, from the perspective of real-world HCPs. To our knowledge, this is the first literature review to systematically assess the implications of EHR design for these outcomes.

Upon stratification based on user group, three of the studies included in our review found that attending physicians rated EHR design more positively, versus other physicians and HCPs [57, 76, 86]. However, Duhm et al. noted that occupational group was not a significant predictor of overall satisfaction with mobile EHRs [76]. Indeed, Mishra et al. reported that satisfaction with EHR vendor design was higher for nurses in one university

Table 2 Mixed methods appraisal tool assessment for the 32 included studies

		Yes		No		Cannot tell	
	n	**n**	**%**	**n**	**%**	**n**	**%**
1. Qualitative studies	8						
1.1. Is the qualitative approach appropriate to answer the research question?		8	100				
1.2. Are the qualitative data collection methods adequate to address the research question?		2	25			6	75
1.3. Are the findings adequately derived from the data?		8	100				
1.4. Is the interpretation of results sufficiently substantiated by data?		8	100				
1.5. Is there coherence between qualitative data sources, collection, analysis and interpretation?		8	100				
2. Quantitative randomised controlled trials	3						
2.1. Is randomization appropriately performed?		3	100				
2.2. Are the groups comparable at baseline?		2	67	1	33		
2.3. Are there complete outcome data?		1	33	2	67		
2.4. Are outcome assessors blinded to the intervention provided?		1	33.3	1	33.3	1	33.3
2.5. Did the participants adhere to the assigned intervention?		3	100				
3. Quantitative non-randomised studies	9						
3.1. Are the participants representative of the target population?		9	100				
3.2. Are measurements appropriate regarding both the outcome and intervention (or exposure)?		9	100				
3.3. Are there complete outcome data?		6	67	3	33		
3.4. Are the confounders accounted for in the design and analysis?		9	100				
3.5. During the study period, is the intervention administered (or exposure occurred) as intended?		9	100				
4. Quantitative descriptive studies	6						
4.1. Is the sampling strategy relevant to address the research question?		5	83			1	17
4.2. Is the sample representative of the target population?		6	100				
4.3. Are the measurements appropriate?		5	83			1	17
4.4. Is the risk of nonresponse bias low?		2	33	3	50	1	17
4.5. Is the statistical analysis appropriate to answer the research question?		5	83			1	17
5. Mixed methods studies	6						
5.1. Is there an adequate rationale for using a mixed methods design to address the research question?		6	100				
5.2. Are the different components of the study effectively integrated to answer the research question?		6	100				
5.3. Are the outputs of the integration of qualitative and quantitative components adequately interpreted?		6	100				
5.4. Are divergences and inconsistencies between quantitative and qualitative results adequately addressed?		6	100				
5.5. Do the different components of the study adhere to the quality criteria of each tradition of the methods involved?				4	67	2	23

hospital, and higher for physicians in another [60]. In addition, seven studies provided participant information regarding EHR experience [58–60, 62, 64, 79, 81], with the number of years of experience varying between studies. Kim and Lee found that participants who had used a smartphone-based EHR for more than a year tended to have a more positive perception of mobile EHR usage [59]. Similarly, Exeni-McAmis et al. reported that the highest rating for a documentation method was given by physicians who had the most experience with the method in question [78].

More generally, the inadequate design of EHRs remains a key driver in clinician burnout [90]. Indeed, with almost 50% of US physicians reporting symptoms of burnout, improving EHR design is fast becoming a critical issue in healthcare [91]. While EHR systems that confuse and frustrate providers can have ramifications for individual well-being, a serious risk is also present to their patients, as the impractical design of these systems can result in selection errors, missed patient information and ultimately, patient harm [12, 40–42, 45–56].

Our review showcases the specific design elements that can influence clinicians' desire to use EHR systems and alter the effectiveness and efficiency of these systems. A number of the themes explored in our review have also appeared in studies conducted by Zahabi and Kaber [15],

and Ratwani et al., such as the positive role of customisation and the need for systems that facilitate provider workflows [92]. However, our review also highlights important design themes, including automation, that were not included in the aforementioned papers.

EHR design can support medication safety (e.g. when data entry options are carefully chosen) or hamper medication safety (e.g. when searchability is not prioritised), as shown in our review. Work has also been done by the Institute for Safe Medication Practices, to develop guidance regarding the specific HIT-associated design features needed to mitigate the risk of medication errors, and by the Australian Institute of Health Innovation, to identify design elements within electronic medication management systems, that present safety issues [93, 94]. However, while much headway has been made, both of these institutions recognise that there is still a long way to go, in ensuring that the design of these systems can consistently promote patient safety.

Limitations

The search criteria used in this review was deliberately broad to obtain an extensive range of papers and enhance the generalisability of our findings. However, this a heterogeneous area of research and, through our inclusion of a variety of outcome assessments, some of the nuances of individual EHR systems, for example, may have been missed. Similarly, the heterogenous nature of our synthesis and the variation in EHR design approaches employed by our included studies may potentially limit comparisons drawn between these papers.

The inclusion of a various study types, other than RCTs, prevented a traditional meta-analysis from being conducted. Selected papers employed qualitative, quantitative and mixed-methods approaches. While the usefulness of other study designs in assessments of usability/medication safety is well established, a narrative synthesis approach was required, which is associated with some limitations. Indeed, the reviewers' interpretation of the literature is relied upon for the data extraction process, which can create bias. However, a narrative approach permits diverse literature to be synthesised into shared themes, relating to the research question.

Areas for future research

Most of the papers involved in our review possessed a summative study objective and were carried out late in the EHR design cycle, aligning with the findings of previous publications [95]. This reveals scope for EHR evaluations to be performed during the breadth of the design procedure, when usability challenges may be more easily addressed.

Our review also revealed inconsistencies in how usability evaluations are conducted. Most of the studies we included chose to assess user satisfaction via surveys. The majority of these surveys were not conducted using validated tools; the most common existing and validated survey used was the System Usability Scale, which was only utilised in two papers [80, 86, 96]. Indeed, the methods by which these surveys were created was not always described in adequate detail, limiting the generalisability of these studies' findings. Interviews were the second most common method of assessing user satisfaction in this review. Indeed, the qualifications held by the moderator, involved in interview and focus group studies, was typically not included, nor were specific details about procedures used to moderate focus group/interviews [97]. As such, assessing the biases associated with the design of these studies is made more difficult. Additionally, of the usability studies we included, few described the evaluators who designed and conducted the usability evaluation in question. There is a need for these evaluators to have expertise in usability and domain experience, so as to ensure effective appraisal of EHR design, yet the level of expertise and domain knowledge of these individuals was not consistently disclosed [98, 99]. As a result, appraising the reliability of these evaluations is made more challenging. Future usability studies should seek to use validated survey tools where possible, and in instances where this cannot occur, should describe a detailed account of the survey creation process. Finally, descriptions of any moderators involved in usability evaluations, as well as their evaluators, should be included in papers reporting on these evaluations.

Trigger tools were the most common medication safety assessment included in this review, followed by incident report review, and while this method is championed by the Agency for Healthcare Research and Quality and the Institute for Healthcare Improvement's, the usefulness of these tools hinges on their sensitivity and specificity [100, 101]. We found that studies did not consistently describe the validation process associated with their tools, thereby limiting our ability to assess their sensitivity [24]. Incident report review is, itself, also inherently associated with under-detection bias, due to factors such as insufficient time for staff to fill out the required forms etc. [102–105]. Future medication safety studies should detail the validation process used for their trigger tool, where applicable, and consider using patient-reported incidents, which may reveal medical safety incidents not captured in staff incident reports [24].

There also appears to be little agreement regarding what exactly constitutes a design element, within an EHR context, with many of the previously published papers and guidelines that discuss EHR design providing

no explanation for why certain features were designated as EHR design elements, while other aspects of an EHR were not [15, 93, 94]. In our review, we circumvented this issue, by using ISO standards, to validate our EHR design elements against. However, using literature from other industries, rather than from the healthcare sector, is less than ideal and represents an important area of consensus building.

Of the studies we reviewed, none assessed the overall health impact on patients (both positive and negative), of EHR design changes. While this may be partly due to our review's more narrow focus on 'medication safety'—thereby resulting in a search criteria that did not capture patient health more broadly, as it relates to EHR design—this still constitutes an important area of future research. Similarly, our review did not identify studies, meeting our inclusion criteria, that evaluated over-the-counter medicines, herbal medicines etc. Indeed, issues regarding if/how non-prescription medicines are documented in EHRs has become increasingly recognised in the literature [106, 107], and further work is needed to improve the recording of non-prescription medicines in EHRs, such that the impact of EHR design on the safe use of these medicines can be assessed.

Finally, the Academy of Medical Royal Colleges have described "a lack of understanding of the differences in the practical reality of working on the other side of the interface", regarding EHRs being shared between primary and secondary care [108]. While this is an area of emerging research, it would certainly seem a useful exercise to compare primary and secondary user requirements of an EHR and gain an understanding of the reasons behind areas of overlap and deviation, as this may assist in optimising transfers between levels of care. Usability requirements can also vary depending on the department, purpose of work etc. and while there were a range of participant types present across the studies, there was an overall lack of detail that would have supported additional stratification. Further exploration of the subtleties between different areas etc. constitutes an area of worthwhile research.

Conclusions

The design of EHRs can enhance or undermine usability and medication safety, depending on the searchability and customisability of these systems, how data entry processes and provider workflow are facilitated and how automation, user guidance and interoperability are implemented. Future EHR evaluations should be performed throughout the design process and further research is needed to enable the development of guidance regarding what exactly constitutes a design element, within an EHR context.

Abbreviations

CDS	Clinical Decision Support
CI	Confidence Interval
CPOE	Computerised Provider Order Entry
DDI	Drug-Drug Interaction
EHR	Electronic Health Record
eMAR	Electronic Medication Administration Record
EMR	Electronic Medical Record
HCP	Healthcare Provider
ICU	Intensive Care Unit
ISO	International Organization for Standardization
IQR	Interquartile Range
MMAT	Mixed Methods Appraisal Tool
NuHISS	National Usability-Focused HIS Scale
QUIS	Questionnaire for User Interaction Satisfaction
SMART on FHIR	Substitutable Medical Applications, Reusable Technologies on Fast Healthcare Interoperability Resources
SSE	Serious Safety Event
SUS	System Usability Scale
UI	User Interface
WPOE	Wrong Patient Order Entry

Supplementary Information

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Supplementary Material 1.
Supplementary Material 2.
Supplementary Material 3.
Supplementary Material 4.
Supplementary Material 5.

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Authors' contributions
The review and narrative synthesis were carried out by MC, who was the lead in writing the manuscript. A second review was provided by SC, during all stages of the review process. SC also provided assistance in the search strategy development. Feedback concerning the narrative synthesis procedure was provided by BC and SC. All authors contributed to the writing of the manuscript.

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Data availability
Template data collection forms, data extracted from included studies and data used for analyses are available from the corresponding author on reasonable request.

Declarations

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Not applicable.

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Competing interests
The authors declare no competing interests.

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