Review

Human–computer interaction in healthcare: Comprehensive review

Meher Langote[1], Saniya Saratkar[1], Praveen Kumar[2,*], Prateek Verma[3], Chetan Puri[4], Swapnil Gundewar[3] and Palash Gourshettiwar[2]

[1] Department of Artificial Intelligence and Data Science, Faculty of Engineering and Technology, Datta Meghe Institute of Higher Education and Research, Sawangi (M), Wardha, Maharashtra, India 442001

[2] Department of Computer Science and Medical Engineering, Faculty of Engineering and Technology, Datta Meghe Institute of Higher Education and Research, Sawangi (M), Wardha, Maharashtra, India 442001

[3] Department of Artificial Intelligence and Machine Learning, Faculty of Engineering and Technology, Datta Meghe Institute of Higher Education and Research, Sawangi (M), Wardha, Maharashtra, India 442001

[4] Department of Computer Science and Design, Faculty of Engineering and Technology, Datta Meghe Institute of Higher Education and Research, Sawangi (M), Wardha, Maharashtra, India 442001

* **Correspondence:** Email: praveenk.feat@dmiher.edu.in.

Abstract: Technological advancements have fundamentally transformed healthcare systems and significantly altered the interactions between medical professionals and information interfaces. This study provides a comprehensive review of the role of human–computer interaction (HCI) in healthcare, emphasizing the importance of user-centered design and the integration of emerging technologies. The paper reviews the evolution of healthcare interfaces, exploring key assumptions in foundational HCI principles and theoretical frameworks that guide the design processes. The analysis delves into the application of HCI principles, particularly user-centered approaches, to enhance feedback mechanisms, ensure consistency, and improve visibility within medical settings, all of which contribute to creating practical, usable, and memorable interfaces. The review provides an overview of successful and unsuccessful cases, demonstrating what determines efficacy in healthcare interface design. The discussion extends to cover the role of interactive interfaces in streamlining clinical workflows, facilitating communication and collaboration, and supporting informed decision-making among healthcare providers. This paper focuses on historical views and milestones of interface design, emphasizing the significance of interactive interfaces. The discussion extends to cover the role of

interactive interfaces in streamlining clinical workflows, facilitating communication and collaboration, and supporting informed decision-making among healthcare providers. Further, the review concludes with an examination of future trends in HCI for healthcare, particularly focusing on the rapid integration of emerging technologies and their implications for the ongoing evolution of interface design in this critical field.

Keywords: human–computer interaction; healthcare interfaces; user-centered design; medical information systems

1. Introduction

Traditional healthcare practices, embodied in handwritten notes, face-to-face consultation, and manual recording, are going through tremendous changes. This transformation has been forced by the integration of innovative technologies, bringing the health industry into a digitalization era. Human-computer interaction (HCI) has emerged as the center stage of this paradigm shift. HCI is an interdisciplinary field that examines the dynamics involved in the interaction between humans and computers and how to enhance such user experiences. The application of technology in healthcare is not a recent phenomenon but has been through different milestones [1,2]. Electronic health records (EHRs) were an essential milestone in the mid-twentieth century as healthcare transitioned from pen-and-paper documentation to digital platforms. The shift promised easier accessibility, easier information search, and better cooperation between healthcare professionals. The below Figure 1 shows the fundamental components of HCI.
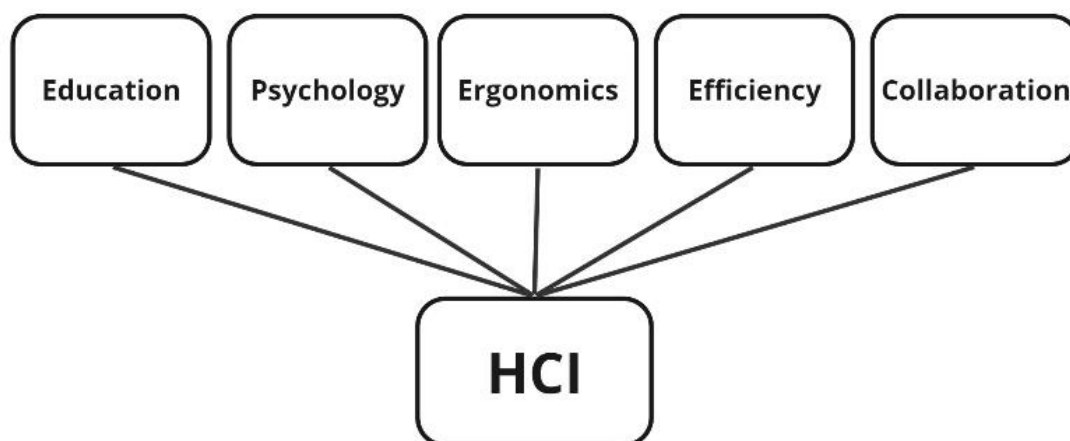

Figure 1. Components of HCI.

Nevertheless, the increasing adoption of technology in healthcare processes is complex. The speed of digitization brings numerous digitized tools for different roles in the healthcare environment [3]. Diagnostic equipment and patient management systems are included among these tools, and a re-assessment of medical practitioners' technology usage is required. Therefore, combining these digital interfaces into the existing workflow without much disruption and providing the desired user

experience is the grand challenge [4]. HCI, an interdisciplinary field, focuses on enhancing human–computer interactions to enhance user satisfaction, a highly valued concept in healthcare. Medical professionals regularly use digital interfaces, including EMR systems, diagnostic instruments, and telemedicine platforms [5,6]. These interactions influence the effectiveness of healthcare provision, diagnostic accuracy, and care in general. Healthcare interfaces present many challenges, and HCI principles address these issues significantly. This makes HCI relevant for a medical professional's cognitive and ergonomic aspects [7]. Healthcare HCI leads to better workflow, reducing mental loads in professionals and preventing mistakes, which results in high-quality patient care. In such a demanding industry, the human-centric approach of HCI becomes significant because timely decisions and correct information-seeking are vital [8,9].

Therefore, this review paper will discuss the history and implications of HCI in healthcare, outline future directions, and describe what will become of HCI in future years. In this regard, the primary goals of this review article are intricate. Namely, we aim to look at the current state of interactive interfaces, highlight beneficial cases, and analyze problems associated with medical practice while communicating with digital devices. The paper aims to present an overall assessment of the advantages and disadvantages of the modified healthcare paradigm of HCI. Second, this review article highlights some design considerations and principles to be followed while designing interactive interfaces for medical professionals. Focus areas include understanding the user-centered design methodologies and critical features customized for healthcare settings. The article takes a comprehensive view of these areas and offers practical advice for designers, developers, and other stakeholders in developing user interfaces for healthcare. Lastly, this review aims to contribute toward developing future research paths on HCI for healthcare. It identifies gaps in existing knowledge and points out possible remedies. It also envisages the incorporation of new technologies, thus aiming to encourage other researchers in this direction. It acts as a guideline for researchers, practitioners, and policymakers looking to improve HCI to match the new needs of healthcare systems. In Table 1 below, we discuss the research that has already been done and the gaps between the research.

Table 1. Literature review.

Sr. No.	Title	Objective	Findings
1.	Human-computer interaction applications in healthcare: an integrative review [3]	Providing a thorough overview of the uses of HCI in the healthcare industry integrating human intelligence and explainable artificial intelligence (XAI) with HCI to provide users with transparency.	Improving the usability, safety, and quality of healthcare services requires effective communication between HCI design and healthcare systems.
2.	Innovating healthcare: key characteristics of human-centered design (HCD) [4]	Investigating how HCD may be used in healthcare to enhance patient safety, quality of care, and experience. To provide light on how HCD promotes innovation in the medical field.	Since it focuses on comprehending the requirements, desires, and limits of patients, carers, and healthcare practitioners, HCD is an essential strategy for healthcare innovation.
3.	What are the users' needs? Design of a user-centered explainable artificial intelligence (AI) diagnostic system [5]	Finding and meeting the unique demands of users in the context of XAI systems in healthcare is the main goal of the project. The goal of the project is to create a user-centered XAI diagnostic system that improves usability and transparency for consumers and medical professionals alike.	AI decision-making comprehension, user happiness, and user trust may all be enhanced by a user-centered design methodology. In order to satisfy user demands, the system was developed to give interactive feedback, visual explanations, and transparency of AI models.
4.	The sense of agency in emerging technologies for human–computer integration: A review [6]	Reviewing the idea of sense of agency (SoA) in relation to new developments in HCI is the goal. Authors present a framework to comprehend the interaction between several forms of augmentations (body, action, and consequence) and their influence on the feeling of agency.	Technologies for integrating humans and computers are divided into three categories: result, action, and bodily augmentations. In developing technologies such as Brain computer Interface (BCI), neuroprosthetics, and virtual reality, careful design is essential to maintain user agency, guarantee benefits, and minimize problems.
5.	A systematic review of HCI research in medical and other engineering fields [7]	The goal of the study is to provide a thorough overview of HCI research, with a special emphasis on methods that facilitate learning and training in the engineering and medical domains. It highlights how these interactions may be improved by extended reality (XR) technologies including virtual reality (VR), augmented reality (AR), and mixed reality (MR).	The paper lists several HCI strategies while highlighting the importance of XR technology in engineering and medical education. It acknowledges a tendency toward interactive settings, draws attention to issues including the necessity for user-friendly design and the integration of cognitive sciences, and makes recommendations for future studies to address these issues and further explore the possibilities of XR.

Sr. No.	Title	Objective	Findings
6.	Role of HCI healthcare system in the teaching of physiology and medicine [8]	The paper's main goal is to create and assess a healthcare system that uses HCI to enhance the way physiology and medicine are taught. The purpose of the research is to evaluate the system's efficacy utilizing a range of assessment metrics, such as user happiness, technical services, convenience of use, and instructional content.	According to the study, the HCI-based healthcare teaching system has an overall user satisfaction percentage of 81.87%, is user-friendly with a 95.17% satisfaction rate, and efficiently provides instructional information. The satisfaction rating for technical services was, however, lower, at 63.83%.
7.	Expanding human computer interaction methods to understand user needs in the design process of personal health systems [9]	The paper's goal is to examine these cutting-edge techniques and inspire the medical informatics community to investigate the intricate requirements of target users to build health technology that benefits everyone, including marginalized and underrepresented communities.	The study discovered that cutting-edge techniques, including integrating stakeholders and utilizing popular technologies, aid in comprehending user needs in personal health systems. By bringing to light the real-life experiences of marginalized groups, these techniques guarantee that health technology is made accessible to all.
8.	The role of human computer interaction in consumer health applications: current state, challenges and the future [10]	The goal is to address issues of literacy and culture, investigate the role that technology may play in empowering patients, emphasize the value of participatory design through iterative user testing, and emphasize usability and user-centered design in health apps.	The chapter emphasizes the value of user-centered design in health applications, addresses issues of literacy and culture, promotes participatory design, and integrates sensors and algorithms to deliver timely health information and enable users to take charge of their health.

The literature review identifies a strong connection between HCI and healthcare, highlighting numerous advances and applications in different fields. Several papers emphasize the importance of integrating HCI with new technologies like XAI, VR, and Internet of Things (IoT) in healthcare to improve outcomes, accessibility, and safety. First, the analysis of user studies in the context of user centric design (UCD) in XAI systems underscores the need for an appealing and easily understandable interface that aligns with the user's mental representations, thereby building trust in the model. This alignment is important as the healthcare system increasingly uses AI-based decision support tools, which should be understandable to both clinicians and patients. This review also explores how such methods can be incorporated into systems designed for minority and multimedia medical big data. Such studies stress the necessity for designing more effective and suitable interfaces for different healthcare contexts. For instance, when Kaiser Permanente applied the UCD principles in the design of EHRs, this led to an enhanced satisfaction level among the clinicians, besides cutting down the time spent on documentation by one-quarter (R. Mishra et al.) [3]. This example shows how application

systems based on UCD could match the cognitive workload of healthcare providers, creating more efficient and intuitive user interfaces.

Today, there is a scarcity of case-level or archival data analyzing the strategic and long-term implementation of such technologies in emerging economies. Studies often neglect potential ethical concerns, data privacy, and user control. Empirical studies and comprehensive case investigations could help to explore opportunities and hurdles regarding HCI in the virtual health domain. Additionally, these could help to advance new technologies, benefiting the patient while respecting ethical practices. Several real-world examples explain how theoretical HCI models, like the UCD, or cognitive models have been implemented and used in healthcare organizations. Another successful case was the application of cognitive models in the development of telemedicine interfaces corresponding to users' mental maps; this led to a 40% decrease in users' mistakes during teleconsultations (M. D. Ekstrand et al.) [11]. Furthermore, the use of cognitive load theory in the design of VR-based rehabilitation systems in stroke patients led to improved patient compliance with therapy (W. E. Macka et al.) [9].

Most of these systems succeed by matching task difficulty to the patient's capacity, with more effective outcomes than conventional approaches. These examples show how applying cognitive theories in HCI can improve the usability and safety of the patient both in theory and in practice. However, not all HCI frameworks have been successful. Efforts to promote AI-based decision support systems in clinical settings encountered challenges due to a lack of intuitive interfaces that align with the clinicians' ways of working (M. Melles et al.) [11]. This case study underscores the importance of adhering to strict UCD procedures and conducting multiple tests before deployment, illustrating how theoretical incompatibility may result in practical failures. It underlines the need to cast a bridge between theory and practice with careful design progression.

2. Foundations of HCI

2.1. Key principles of HCI

HCI brings together how humans behave and what technology can do. HCI is based on a few main rules that are important for its usefulness and strong connection to users. These help to guide HCI workers, in describing the functioning of interaction design. In the extensive field of HCI, these central ideas cover a range of fundamental concepts. Designing for the user is an essential part of HCI. Factors like feedback timing, visibility, and learnability work together to create interfaces that prioritize user experience [10]. These principles go beyond the finer details. Melles et al. [11] studied the behavior of technology users, aiming to make screens that smoothly align with natural human interactions with devices. Their study demonstrated how human–technology collaboration can come together to accomplish complex tasks in innovative ways [11].

2.1.1. User-centric design in HCI

HCD in HCI is a crucial method of design that places paramount value on human end-users, tackling their needs, likes, and abilities when building interfaces or systems. It focuses on creating technician skills and methodology that is simple, user-friendly, and smoothly embedded into the user's routine. The user-focused design involves research, testing, and iteration of the design toward a wide

variety of users. HCI centers on the user, who is the creator of the interface. Therefore, their role is crucial regardless of the purpose [10].

User-centric design, also called user-centered design, is an iterative design approach that is based on the goal of meeting or exceeding the needs, behaviors, and preferences of users by involving and informing their active participation, starting from specifying the requirements of the application through testing and evaluation of the product before its release. Various methods are employed within this phase, such as user interviews, group discussions, and surveys, designing prototypes, testing, and making revisions. The final goal of user-experience design is to create an easy-to-use, fast, and pleasant interface or product [12].

The design of products from a user-oriented perspective is based on the different backgrounds, levels of expertise, and specific goals and proficiency of users. Interface designers may miss the mark if they do not properly account for users' needs, leading to unclear, irritating, and unusable systems. Interface design with a user-centric approach assists in solving these hurdles as it guarantees that particular interfaces are adapted to the user's cognitive capabilities, preferences, and tasks [9]. Through offering this service, the user's satisfaction improves and productivity increases, resulting in better quality.

User-centered design should be a main focus as it is a prerequisite for creating simple and easy-to-use controls. Consequently, it eliminates the need for extensively training and supporting users. In addition, it increases user satisfaction and engagement as the design matches their expectations and preferences. Lastly, user-centric design can lead to a swift and accurate process. In addition, taking into account the requirements of different users, including disabled people and those with varying levels of technological knowledge, improves inclusivity. Below Figure 2 shows the phase of user centric design (UCD), which are the steps to create a user centric interface.
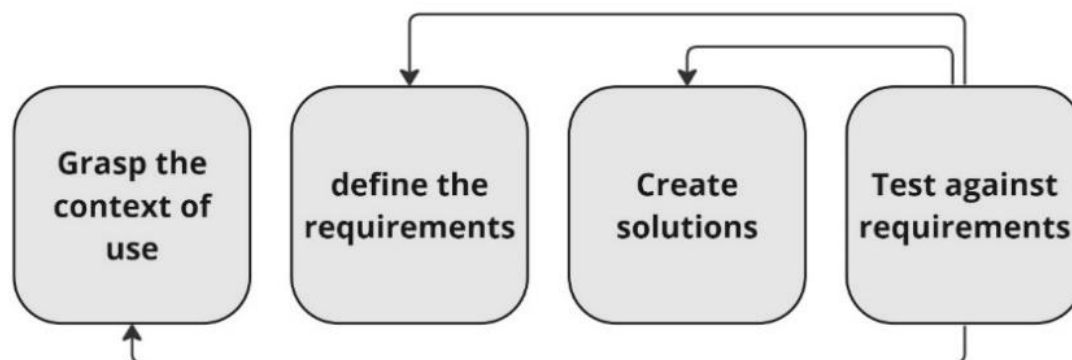

Figure 2. Phases of user-centric design.

A user-centered approach to design relies heavily on HCI methodologies, tools, and frameworks for collecting data on user behavior, analyzing the interface performance, and making iterative improvements to the HCI design solutions [13]. HCI practitioners and researchers use different techniques, including user interviews, surveys, usability testing, and cognitive walkthroughs, to collect data on user needs and preferences. They also work on design ideology, regulations, and heuristics, which are based on psychics. In addition, HCI covers the study of interactions between humans and computers, interface metaphors, and techniques that can be utilized to enhance usability and user experience [11].

User-centric design means that users' wants and needs are at the interface's core, making it more usable, satisfying, and productive. By involving users' reviews and recommendations in the design process, user-oriented design helps uncover and deal with usability challenges upfront, meaning less labor-intensive redesigning or fixing problems after the product's launch. Moreover, it brings a user-oriented culture into the organization and drives the organization to continuous improvement of new products and innovations. In a nutshell, user-centric design improves users' engagement with the devices, because they are usable and enjoyable [12].

2.1.2.   Feedback and responsiveness in HCI

Feedback and responsiveness are two essential components of HCI that contribute to a good user experience and system performance, thus playing a key role in HCI. Feedback refers to the process through which the system transmits information about the success or the result of the user's action. It is related to the speed of response, while responsiveness refers to the system's ability to react promptly and efficiently to the users' input or requests [13]. HCI involves diverse modes of user–system communication, in visual, auditory, and haptic forms. These modes let users know if an action is completed, the system is in a particular state, an error has occurred, or progress is being made. Responsiveness, on the other hand, pertains to the system's prompt reaction to user input, ensuring users receive timely feedback and can interact with the interface without interruption.

Feedback and responsiveness are required to improve user engagement, satisfaction, and productivity. They make information accessible for users, guard against misdirection, and instill trust in the system [9]. User engagement and satisfaction can decrease if there is not enough help, leading users to feel lost, frustrated, or confused about what their actions will produce. Similarly, prompt responsiveness ensures all inputs and outputs from users are quickly answered so that they do not experience delays or disruptions in their workflow. Comments and reactions are mandatory to construct an interface that may satisfy users and predict their future preferences and reactions, contributing to a better user experience by being precise in instructions, reducing doubt, and eliminating errors. Feedback builds trust in the system and increases the user's understanding, while responsiveness smoothens the operation and leads the process to be user-friendly [14].

Feedback and responsiveness can take various forms, including:

(1) Visual feedback: visual clues like the progress bar, pop-up messages, or interfacial changes showing the system's status or how it has reacted to the user's input.

(2) Auditory feedback: sounds or music are used as auditory cues like warning messages, positive confirmation, and error signals.

(3) Haptic feedback: haptic feedback in the form of vibrations or pressure can make people feel the system as more real; touch and interaction can also be more precise and intense.

Haptic feedback represents a group of tactile sensations that the system uses to transmit information or reinforce the interaction between the system and the user. It provides users with kinesthetic feedback, through pulses and resistance, to make them feel more in touch with their surroundings and increase engagement. Haptic feedback is the most reliable way for users to know the devices when there is no or limited access to visual and sound feedback, such as in mobile devices and virtual reality [11]. HCI is crucial in developing and integrating well-managed response and feedback mechanisms in interactive systems. HCI researchers and practitioners use user-focused design processes, usability tests, and iterative design methods so that the feedback mechanisms can be natural,

insightful, and directed at users' needs. By applying feedback and user ratings as well as their ideas, HCI enables the development of interfaces that provide quick, adequate, and useful feedback, increasing usability, user satisfaction, and the general user experience [14].

2.1.3. Consistency and visibility in HCI

One of the guiding pillars of HCI is consistency and visibility, which are intrinsic to the interface's usability and utility. Consistency describes an ability to match design, words, and functions on different parts while constructing an interface or system. On the other hand, visibility relates to making relevant information and functionality easily discoverable and available for the users. Together, these principles provide users with confidence in the navigation, familiarize them with its functionality, and maximize performance by enabling them to execute tasks effectively [15].

Consistency and visibility use the same elements, such as design, terminology, and interaction patterns, consistently throughout the interface—keeping a uniform layout, color schemes, iconology, and navigation schemes, to make the interface easy to use and predictable. Visibility relates to having important controls and functionalities visible, accessible, and easily understandable to the users. This may involve labeling items, placing all buttons in a prominent location, and providing users with a straightforward navigation path to find and interact with important elements [16].

Consistency and visibility in HCI are essential to ensure that users can anticipate and master certain interactions. Consistency lowers the cognitive load by supplying users with similar patterns and clues, making it possible for them to learn how to use the interface and perform different tasks with the same ease on every occasion. Visibility allows users to do what they want in one click or tap, sparing time and effort for task completion [12,17]. Without consistency and visibility, users' expectations can be negatively affected as they begin to feel confused or frustrated, negatively affecting perceived usability and satisfaction. In Table 2 below, we discuss the work related to consistency and visibility in HCI.

Table 2. Consistency and visibility in HCI.

Aspect	Description	Need	Role of HCI	Example	References
Consistency in HCI	Maintaining uniform design, terminology, and actions across interfaces to ensure predictability and easy use.	Ensures ease of learning and reduces cognitive load.	HCI principles guide designers in creating consistent interactions, reducing the mental effort required to navigate the interface.	A health record system that uses uniform data entry forms and consistent navigation menus.	[13,14]
Visibility in HCI	Making important information and system status visible and easily accessible to users.	Enables users to quickly find information and understand system status.	HCI focuses on designing interfaces that highlight critical information and ensure that users can see what actions are available and what the system is doing.	A patient portal that prominently displays appointment schedules, medication reminders, and test results.	[14,15]
Need for consistency	Consistent design helps users build familiarity with the interface, reduces errors, and enhances the overall user experience.	Reduces the learning curve for new users and helps experienced users navigate more efficiently.	HCI ensures that all elements of the interface adhere to a common design language, making transitions between different parts of the system seamless.	Consistent color schemes, icons, and terminology across all parts of a hospital's electronic health record system.	[15]
Need for visibility	Visible information and controls improve user satisfaction by providing immediate feedback and reducing the effort needed to find critical information.	Enhances usability and helps users make informed decisions quickly.	HCI helps prioritize the placement and prominence of information and controls, ensuring users can find and understand them immediately.	Dashboards in healthcare management systems that show real-time data on patient status and hospital resource allocation.	[14,15]

Human–computer interaction stands out in this area because it facilitates the creation of consistent and visible user interfaces. Human–computer interface designers and developers rely on user-centered design principles, heuristic evaluation, and usability testing methods to ensure interfaces are built upon consistent patterns and important parts can be noticed. By implementing design processes of iterations and users' feedback, HCI can explore whether the interface has inconsistencies or is unclear and work to revise it to improve consistency and visibility [18].

Consistency and visibility improve the usefulness and usability of interactive systems in the following ways. First, due to continuity, users feel good, and the cognitive work is reduced while completing the actions. This results in a speedier learning curve and higher efficiency, as users understand the interface without much effort and can execute tasks easily. Next, visibility will help

users locate and use information or functionality quickly and easily, reducing errors and discomfort. By designing interfaces with consistency and visibility principles, HCI professionals create user-friendly experiences that enhance usability, satisfaction, and user engagement [15,19].

2.1.4.   Adaptability and error avoidance in HCI

Adaptability and error prevention are the basic concepts of HCI, creating extra features to provide flexibility and tools for the user to avoid or correct errors during the interaction with the interface. Adaptability provides the basis for the interface to allow users to adjust it to their particular circumstances [20]. On the contrary, error avoidance is geared toward building an interface that limits error occurrence; whenever such errors occur, it provides users with the tools to enhance error detection, correction, or poor-quality recovery [16].

Adaptability in HCI refers to the interface's responsiveness to accommodate different users, capabilities, and environmental features. This may involve customizing, personalizing, or adapting the systems to meet user input or specific system requirements. Contrasting with error avoidance, this technique is targeted at developing logic to avoid or minimize errors that can happen during interaction [21]. This includes various error prevention features, such as error detection techniques and recovery mechanisms, to decrease the influence of errors on user experience and system functioning. The need for flexibility and failure avoidance in HCI arises from the many users, situations, and tasks encountered in real-world usage scenarios. People use digital products and services differently and with varying levels of ability and expertise. This means that interfaces need to be designed in such a way that they are flexible and able to suit all users' needs [17]. Errors may occur due to various reasons, including end-user mistakes, system malfunctions, or environmental conditions. This demonstrates the necessity of error avoidance techniques to maintain usability, readability, and end-user trust.

HCI performs an essential function in connection with interface development, including adaptability and error prevention. HCI experts use user-centered design approaches, usability testing, and iterative design processes to understand users' needs, desires, and potential error situations. With the help of the users' feedback and insights, HCI guarantees that interfaces are provided with flexible and configurable features and error prevention, which are precisely what users expect [22].

Adaptability and error prevention are the major subgroups of usability, which include reliability and user satisfaction, as users will be able to choose what they prefer and use the interface accordingly [11]. These features improve the user's interaction with the application or program and increase the user's experience. Likewise, error avoidance techniques help to eliminate or alleviate problems, which may frustrate users. Additionally, they ensure the interaction is correct and readable [17]. In Table 3 below, we discuss the key HCI principle in applied health design and its applications.

Table 3. Key HCI principles applied in health design.

Sr. No.	HCI principles	Application in healthcare design	References
1	User-centered design	Prioritize the needs and preferences of healthcare professionals and patients, aligning the system with their workflows.	[16,18,19]
2	Feedback and response time	Implement timely and informative feedback mechanisms to keep users, especially medical professionals, informed.	[6,20,21]
3	Consistency	Keep a regular look and way of interacting with healthcare tools for a unified user feeling.	[10,22–25]
4	Visibility	Ensure relevant information is visible and easily accessible within healthcare interfaces, enhancing transparency.	[11,22,23]
5	Learnability	Design intuitive interfaces that are easy to learn, supporting quick adaptation by medical professionals.	[12,24,23]
6	Flexibility	Provide customization options within interfaces to accommodate diverse user preferences and workflows.	[6,12]
7	Error prevention and recovery	Incorporate features to prevent errors and provide clear messages with easy-to-follow recovery mechanisms.	
8	Efficiency	Optimize workflows and interactions within healthcare interfaces to streamline tasks for medical professionals.	[5,10]
9	Memorability	Design interfaces with consistent layouts and visual cues to facilitate easy recall and use by medical professionals.	[2,26]
10	Accessibility	Ensure that healthcare interfaces adhere to accessibility standards, providing inclusive access for users with diverse abilities.	[6,8,10]
11	Hierarchy of information	Organize information hierarchically, prioritizing critical data for easy access and informed decision-making.	[11,16]
12	Task analysis	Conduct task analyses to understand the specific tasks and workflows of healthcare professionals, guiding design decisions.	[11,13]
13	Usability testing	Do tests with real users to find and fix usability problems for practical everyday needs.	[16,19]
14	Collaborative design	Encourage collaboration between designers, healthcare professionals, and patients throughout the design process.	[12,14]

2.2. Theoretical frameworks in HCI

HCI is a complex and diverse subject that combines the study, creation, and careful testing of screens and keyboards for computer use. Additionally, it carefully analyzes how people interact with computers, exploring the connection between humans and machines [27]. HCI is about more than just combining technology and user experience—it aims to understand how humans interact with technology and improve the construction of smooth and easy-to-use interfaces. In this complex world, theory-based ideas become crucial. They offer organized designs and understandings that help researchers and designers decode user's actions [28,29]. These plans, like building designs, show how people act and give designers a set of tools to create user-friendly screens. These methods are essential

for researchers to understand user actions and make good design choices. They also help them judge how well these systems work for users. In the following parts, we study important ideas in HCI. We will examine why these ideas are so important and give real-life examples of how they can be used in actual designs. This will clarify how it all fits with what people do daily. As we move through these ideas, it is clear they are not just theories; instead, they are helpful ways for designers to create interfaces that match how humans think and interact in real life [23,30].

2.2.1. Cognitive models: Unraveling mental processes

In the complex world of HCI, thinking models are fundamental. They help us understand how people take in information and make choices when using computer interfaces. A model often used is GOMS (goals, operators, methods, and selection rules). This model provides a detailed look at what users do, helping to understand complex thinking. When planning healthcare, in which being careful and making intelligent choices are crucial, knowing how doctors think becomes necessary. Making a healthcare help system using the GOMS model could improve how doctors make decisions [31]. The below Figure 3 shows GOMC which is used in cognitive models.
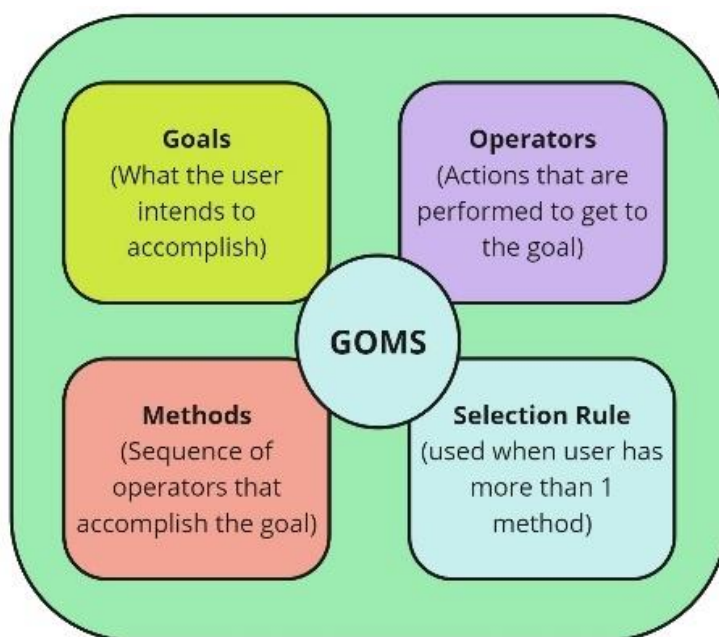

Figure 3. GOMS model (goals, operators, methods, and selection rule).

In this situation, the GOMS model can help to examine how doctors think and make decisions, breaking down their actions into clear parts, starting from big goals in taking care of patients to specific methods and treatment choices. The website becomes an automatic part of doctors' decision-making, giving alternatives like suggested cures based on what they want to accomplish (like checking a patient's health) and pre-set rules. By using the GOMS model, the system improves how doctors make decisions. It does not bombard them with extra information; instead, it helps their thinking process. The screen, listening to their aims and efforts, makes decision-making simpler and helps with better health choices [32].

An example of the application of this model was demonstrated in a case in which GOMS-based clinical decision support system (CDSS) was used in a large hospital environment to diagnose heart ailments. Clinician activity was monitored, and the interface changed depending on the stage of the diagnostic process to present information that would be most useful at that time. For example, in the initial patient assessment screen, the system suggested vitals and patient history; in the decision-making screen, it recommended diagnostic information and effective management strategies. Applying cognitive models such as GOMS in healthcare proved the effectiveness of the suggested approach, as diagnostic mistakes were reduced by 30%, while clinician satisfaction with the decision-making improved [33].

Furthermore, there is evidence of the effectiveness of applying cognitive models in telemedicine applications that allow effective remote consultation. In W. E. Macka et al. [9], it was shown how integrating cognitive load theory helped in enhancing users' experience by reducing unnecessary material and organizing clinicians in a systematic consultation model. This design strategy was useful for regulating more intricate, sequential engagements such as home and remote monitoring of patients with chronic health conditions, wherein the system was configured to supply the subsequent actions depending on the current clinician's cues. Apart from discouraging hassles as well as promoting effectiveness within consultations, this practical application of cognitive models improved clinical effectiveness by enhancing effective delivery of the analysis.

On the other hand, sometimes the success of system design does not match the cognitive models, providing an inferior result. An example is a hospital that adopted an AI diagnostic tool without understanding the clinician's cognitive processes, thereby leading to rejection and non-use of the system (M. Melles et al.) [11]. Additionally, the tool's interface had too much unnecessary information and discarded the clinical perspective. This makes it clear that cognitive models should be used in the design phase in order to prevent users from being hindered by the very system that is supposed to help them.

Other models, such as the cognitive task analysis (CTA), have also been used in the design of interfaces that support healthcare staff's cognitive processes. For instance, a CTA was employed in developing a medication administration system that informed nurses of possible interactions by taking into consideration both the sequence of tasks and the thinking process during patient rounds. The cognitive model was applied to a leading healthcare facility and resulted in a 25% decrease in medication errors and enhanced response times. This is an example of how cognitive models can be used to bridge the gap between theory and practice (M. Melles et al.) [11].

2.2.2.   User mental models: Bridging perception and interaction

Users' ideas about how things work guide them in understanding and using a system. When making a system, matching its design with how users think will make it easier to use. When working on the details of healthcare design, especially making a patient portal, designers try to match how patients typically think about their health information [26,34]. The main goal is to arrange the portal's design and set it up in a way that connects with what patients understand, to make it easy and automatic for people to get medical information. To do this, designers work with patients to determine their thoughts on obtaining medical records. This means talking to users and learning about what they think, like, and expect. By learning how patients feel about and use their medical information, designers can easily change the website's structure and navigation to match their ideas. The plan creation goes beyond looking good and working well—it becomes a team effort with the people who will use it.

Designers, who get information from talking to users, carefully make the steps and look of the patient portal so it is easy for people to understand. This careful arrangement makes it easy for users to use the portal without much thinking, eliminating extra mental challenges [34,35].

In the conceptualization of healthcare systems, particularly methods like patient portals, aligning the structure of the system with users' mental models significantly enhances user experience and practical outcomes. A study by R. J. Holden et al. [26] emphasized the importance of designing systems that resonate with users' cognitive frameworks, thereby facilitating more intuitive interactions and improving overall system usability. Research on mental healthcare has shown how patient portals should reflect users' mental models to enhance the utility and effectiveness of care delivery. Researchers interviewed users and conducted focus groups to identify the mental models of patients in advance of their interaction with the mental health data. From this understanding, the portal was redesigned, with "Therapy Notes" and "Medication Update" sections that resonated with the patients' mental maps. This strategy was effective, as patients were more empowered, leading to the conclusion that when technology is in harmony with the user, it not only makes it easier to use but also improves the health of the mind [26,36].

2.2.3. Activity theory: Understanding social context

Activity theory, a big part of HCI, helps us focus on the complex social and teamwork aspects of technology used by people. This idea examines how people's actions are closely connected to social and cultural situations. In healthcare, which is all about working together for good patient care, activity theory becomes a critical guide to correctly designing screens or interfaces. The main idea of activity theory is that people's activities go beyond single tasks. They are connected to how healthcare teams work together while doing their jobs. According to activity theory, the success of healthcare delivery does not just depend on a person's actions. It also needs teamwork and is linked deeply with our social and cultural groups. Since healthcare teams work together, activity theory is crucial for creating interfaces that help them quickly talk and solve problems. Here, the theory tells designers to examine how healthcare workers do their societal jobs. It makes us look beyond what we need technology-wise, pushing for a deep understanding of how communication, sharing information, and making decisions work in healthcare [36].

Imagine creating a team health project using activity theory. Designing requires deep knowledge about where healthcare workers do their jobs. The interface, designed with the help of activity theory, is more than just a place to keep information. Instead, it turns into a live online place where medical people meet. They talk in real-time, quickly share information, and participate in making decisions.

2.2.4. HCD: Integrating user involvement

In simple terms, HCD is a way of thinking that always sees the users as the most essential part of the whole design process. HCD supports the active involvement of users, creating a process focused on understanding and improvement. This is achieved through constant feedback from users. In the world of healthcare design, user-centered design becomes a central idea. This is especially important when making interfaces that meet the different needs of people who use healthcare services. For example, when making a health app for patients, using patient-centered design is very important. This means a continuous and back-and-forth connection with patients during the planning time. Usability

testing, feedback meetings, and constant improvements are essential to the HCD method. The final result is not just an app—it is a thing that connects with and meets the unique requirements of patients. By accepting the idea of HCD, healthcare designers make sure that the people who use those services are involved in improving them. This teamwork method results in more than just the system working. It becomes a way to put users first, matching with what they want and like. HCD shows how including people in technology for healthcare can change things. It helps create helpful tools that understand and support the human experiences they want to improve [26].

Omaghomi et al. [36] proved this idea by evaluating a mental health app that aims to help patients with chronic diseases. Users' engagement on an ongoing basis not only pointed out the app's effectiveness in terms of supporting user experience but also contributed to improved patients' satisfaction and compliance with the proposed treatment regimens. Following feedback and modifications at every step, it was possible to improve the working of the app to support the patient's health and improve the overall health conditions [36].

2.2.5.   Information processing models: Enhancing information flow

Models for information processing are the basis of HCI. These use computer interfaces to study how people see, understand, and handle information. These patterns become useful in healthcare design, where organizing and showing medical information is very important. The main goal is to match how to offer information with what users think so they can understand it quickly and easily. In making a medical information screen for doctors aided by an information processing model, the model arranges patient details, ensuring essential data is arranged sensibly and clearly shown with proper order. In real life, information architecture is a vital part of this plan. This ensures that data flows smoothly with people's thinking processes. This creates a health dashboard that shows and organizes data to help doctors handle information quickly and adequately. By following information processing models in healthcare design, interfaces become more than places to store data. They change into active places where information is shown carefully, respecting how users see and understand data. This way, information processing models help to improve how data moves. It makes sure important healthcare information is available and easy to understand in a way that fits the brains of the people using it [37,38].

2.3. Significance of HCI in healthcare environments

In the dynamic sphere of medicine, human touch and technological progress intersect to reinvent how patient care is given and received. At the core of this metamorphosis lies HCI, a multidisciplinary field where human behavior meets technology design. The importance of HCI in healthcare environments is profound, signaling the advent of patient-oriented care services, efficient treatment processes for healthcare providers, and the most effective medical practices achieved through the purposeful integration of interactive systems. This exploration delves into the various facets of HCI's role in healthcare, revealing its importance, uses, and future potential for transforming healthcare delivery. In healthcare, HCI is not just about the design of interfaces—it is a philosophy that centers humans at the heart of technological interventions [34,39]. It acknowledges that the design of interactive interfaces is fundamental to the effective delivery of healthcare and patient success. HCI in healthcare fundamentally revolves around aligning the intricate interplay between humans and technology. A thoughtful design aims to simplify access to healthcare information and facilitate

communication for healthcare professionals and patients who are passionate about providing care. The primary goal of HCI in healthcare is the production of interfaces that are not only easy to use but highly attuned to the intricacies and sensitivities of medical practices. Whether it is the design of patient portals, EHRs, medical devices, or telehealth platforms, HCI principles become the compass guiding the creation of interfaces that resonate with our human experience [38,40].

2.3.1. Empowering patient-centric care

Patient-centered design in HCI in healthcare is a crucial part of this field, with the main goal of developing interactive interfaces that help patients in their decision-making processes and actively participate in their own care. This strategy acknowledges patients as the subjects of their healthcare journey, who are not only passive recipients but rather active directors willing to utilize the available tools and resources to manage their health and wellness [41]. Empowering-oriented patient-centric care refers to the design and implementation of interactive interfaces in healthcare that embody the concept of patient empowerment and engagement in the making of their own healthcare choices [39]. This category includes the design of patient portals, mobile health apps, and other online platforms that enable patients to access their medical records, communicate with healthcare providers, and actively take part in their healthcare [42].

The importance of placing patients at the center of the care process emerges from the new trend of patient-oriented healthcare delivery models, where patients are seen as co-producers of health services instead of mere passive recipients. Proponents of HCI argue that involving patients in their treatment addresses problems related to personalized care, availability, and patient-centeredness [40]. The strength of HCI lies in its role as a driving force behind patient-oriented care, which is based on HCD methodology. HCI specialists conduct user research, usability testing, and agile design processes to know who the patients are, why they are different, and what they struggle with. Human behavior and data help craft human-computer interfaces, ensuring that the interface is user-friendly, intuitive, and designed to aid patients' mental models and capabilities [43].

2.3.2. Streamlining workflows for healthcare professionals

A patient-focused care platform through HCI leads to improved care outcomes, healthcare provider experience, and a robust healthcare system. They get better entertainment, authority, and participation, leading to higher compliance with treatment procedures and enduring well-being. Medical personnel stand to gain improved communication, collaboration, and patients, leading to better care delivery and joint treatment governance. Besides, the healthcare system helps boost the system's efficiency, decrease overall health costs, and bring better patient results [42,44].
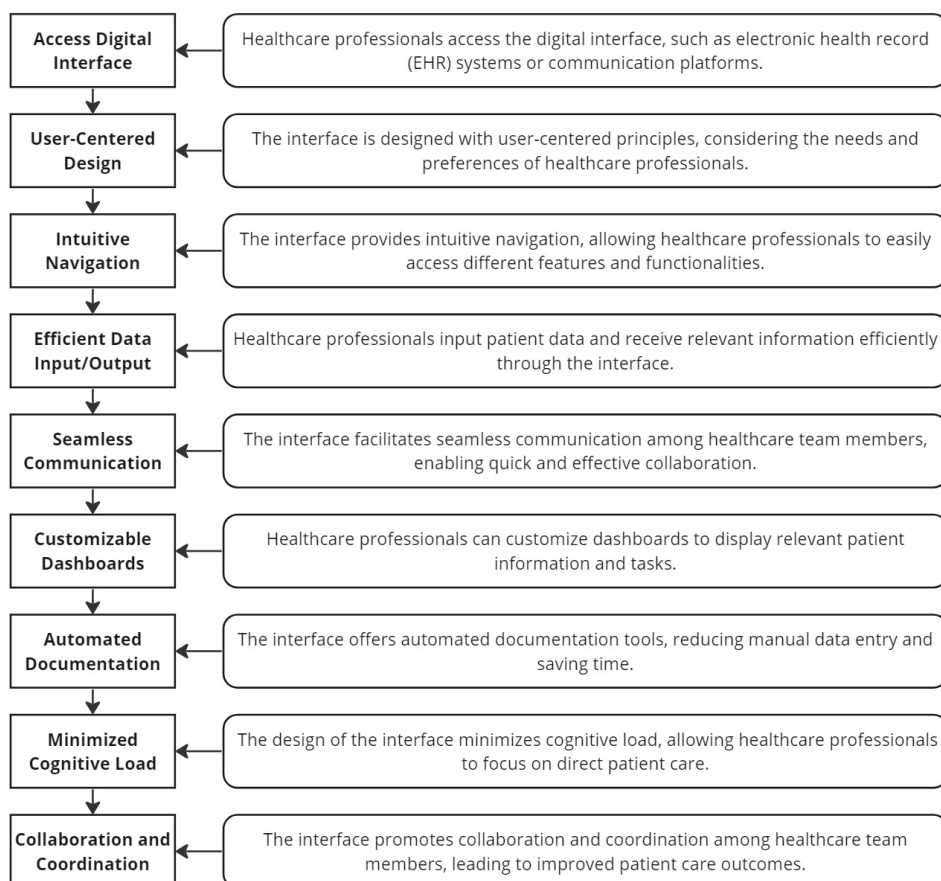
Figure 4. Streamlining workflows for healthcare professionals in HCI.

The above Figure 4 shows the Streamlining workflows for healthcare professionals in HCI. A community portal can be developed using HCI principles to encourage a patient-centric approach toward healthcare. The patient's record can be tracked, appointments can be scheduled, prescriptions can be requested, and communication with healthcare providers can be made safe and secure through this portal [43,45]. The portal interface is laid out in a way that will be easy to understand and navigate, allowing patients to customize their preferences. Patients will be able to use the portal in a simple and friendly way, to check the information given on their health and actively cooperate with the managing of their healthcare. Through this, patients will be responsible for their health, so they will involve themselves in their healthcare journey; as a result, they will have a better health outcome and will be able to develop a more collaborative relationship with their healthcare provider [46].

HCI is at the heart of making workflow management for health professionals easy by using user-centered design in the development of digital interfaces and systems. Healthcare technology professionals carry out user-centered design tasks such as user research, task analysis, and usability testing to understand the particular needs, likes, and problems of healthcare professionals. Human-computer interface acts as a facilitator of this task by creating interfaces that consider the user's common task and decision-making skills and minimize cognitive load, which in turn leads the more efficient and effective workflow processes. One of the main advantages of HCI-based healthcare workflow optimization for both healthcare providers and patients lies in this context [36,47]. The workload of healthcare professionals is more reasonable, the documentation workload is reduced, job satisfaction

becomes more noticeable, and professionals have more time for direct patient care. Patients gain from expanded access to healthcare services, knowing their doctors, and better coordination of services, which results in improved health and satisfaction [48].

2.3.3.   Enhancing the usability of medical devices

The usability of medical devices can be improved by utilizing interfaces and functionalities that are intuitive, efficient, and easy to use for healthcare professionals. Usability, as a concept, includes aspects like task completion time, ease of use, accuracy, ease of learning, satisfaction, and ease of mind. The target is able to design instruments that support healthcare professionals in doing tasks correctly and swiftly, considering the risk of making errors; overload is simultaneously minimized. The urgent demand for improving the usability of medical devices results from their significant contribution to healthcare delivery [49,50]. Medical devices have different uses, such as diagnosis, monitoring, treatment, and patient care. Thus, these tools need to be designed in such a way that the health professionals are the ones to direct their use and flow in the healthcare system. When usability problems appear, there is a high chance for mistakes to be made, efficiency will drop, and health providers will be unsatisfied; the quality of medical services will be influenced, and the safety of patients will be compromised [42].

HCI is essential for creating user-friendly medical devices, offering the application of user-centered design principles to their development. HCI professionals perform studies and testing to unravel the healthcare providers' thoughts, interests, and challenges toward the device's usage [51]. Based on these findings, the design of the interface or the functionality for users should be based on cognitive abilities, workflow, and convenience in actual clinical practice. Improving the user experience of medical devices by making them more user-friendly is one of the main advantages that HCI provides to both healthcare professionals and patients [12]. The adaptable medical devices allow healthcare professionals to do their tasks with improved accuracy and efficiency, yielding better patient safety and health outcomes. By reducing the cognitive burden and avoiding workflow disturbances, HCI improvement in medical device utilization leads to a better quality of care delivery, contributing to a better performance of health systems [46].

Example: Consider patients with suspected cardiac issues attending the emergency department (ED). A small handheld ultrasound device is the device of choice for the physician working there. By using an HCI-based design, the device comes with an easy-to-use touchscreen interface in which the control area is well-organized, with frequently used settings clearly indicated. Moreover, the device is fitted with feedback mechanisms, both visual and haptic, turning it into a robust and easy-to-use device in a typically high-stress clinical environment. As a result, the emergency staff can perform their job properly and do ultrasonography in a short time, resulting in quick and accurate diagnoses and favorable patient management.

2.3.4.   Facilitating telemedicine and remote care

Enhancing telemedicine and remote care means using technology to ensure that healthcare practices and patient-provider communication can occur without physical presence. These distinct services include but are not limited to video consultations, remote monitoring of the patient's health status, and telehealth platforms that assist with remote diagnosis, treatment, and follow-up care. The

goal is to facilitate access to healthcare services regardless of any issues of geographical distance, mobility difficulties, and need for physical presence [39,52]. The necessity of telemedicine and remote care services stems from several factors comprising the ever-growing need to provide controlled and easily accessible healthcare services, especially in areas with a shortage of them. Telemedicine provides a way to improve healthcare accessibility, reduce healthcare inequalities, and provide high-quality healthcare by allowing timely interventions, continuous monitoring, and teleconsultations, among others. Besides, in instances like pandemics or natural disasters, telemedicine remains available even if other healthcare services are temporarily shut down, ensuring continuity in patient care [53,54].

HCI has a key role in telemedicine and remote care by aiding the design of interfaces that help deliver effective communication, collaboration, and interaction between healthcare providers and patients in a virtual environment. HCI professionals are often responsible for designing user-friendly interfaces that are easy to navigate, increasing the level of clarity of communication, and keeping a certain touch of humanity in healthcare, even for virtual interactions. By adopting HCI principles, telemedicine interfaces will facilitate a more favorable user experience, patient engagement, and the remote delivery of healthcare of the highest quality [46]. Additionally, HCI-based design ensures that telemedical interfaces are user-friendly and efficient and enable competent communication. This, in turn, results in increased patient satisfaction and engagement in remote healthcare [55].

Example: Examine a telemedicine system for long-distance psychological consultations. The interface accommodates video conferencing, interactive chats, and virtual waiting rooms, which help facilitate easy and safe communication between patients and mental health professionals. Furthermore, the platform also includes tools for virtual screening, mood tracking, and medication reminders, which are intended to support ongoing care in the remote setting. Through HCI-based design, the telemedicine platform makes it easy to provide patients with necessary mental health services online where they feel most comfortable [56].

2.3.5. Iterative design and continuous improvement

Iterative design is the term that describes the process of improving and enriching healthcare interfaces through a repeating cycle of design, testing, and redesign based on user feedback and the changing needs of the users. Through continuous improvement, the usability and effectiveness of health interfaces are improved in the long run. The iterative nature of human–computer interfaces in healthcare defines the continuous requirement for improvement resulting from a perpetually dynamic healthcare setting, where the needs of users, technology, and best practices are constantly developing. Interfaces of healthcare systems need to adjust to changing demands, face novel difficulties, and use existing technologies to achieve high-class user experience and to increase the effectiveness of healthcare delivery [47].

HCI is essential in aiding an iterative design process accompanied by improvements that provide mechanisms, tools, and frameworks used for collecting user feedback and implementing usability testing, based on the user specifications of the user interface. Adhering to HCI principles, including user-centered design and participatory design, helps ensure that the human–machine interface (HMI) is optimized, reflecting the users' continuous progress as well as adaptability to practice changes in healthcare [31]. Design iteration and constant improvement can be of great help in achieving healthcare interfaces that remain relevant, efficient, and user-friendly in the face of the dynamic nature of the healthcare environment. By using patient feedback and coming up with interface designs in iteration

mode, healthcare agencies will be able to support patients' satisfaction, develop care streams, and consequently lead to better patient outcomes [57]. Consequently, ongoing innovation enables seamless information interoperability, where the latest technologies and practices are a key driver of healthcare development [48].

Example: A mobile health application made specifically for diabetes patients. Through continuous improvement and iterative design, the application experience is re-evaluated over regular cycles based on the user's product enhancement request, clinical guidelines, and progress in technology development. Therefore, responses from the user regarding key features like meal tracking or medication reminders are the determiner of additional features that the application can iteratively be designed to include. The customer service effort mainly enhances useability, achieves data security, and integrates AI to improve personalized health insights. Therefore, the mobile health application changes its approach multiple times to achieve users' highest degree of adherence and effective control of diabetes [58].

2.3.6. Ethical considerations in healthcare design

Ethical concepts in healthcare design incorporate issues connected with patient privacy, data safety, informed consent, and ethical decision-making. The ethical design of any healthcare interface requires the integration of patient rights and autonomy and responsible use of technology, resulting in products that are congruent with the ethical principles and professional practice in the healthcare industry. The ethical implications of healthcare design emerge from the privacy and safety hazards raised by the sensitive nature of healthcare data and its use by technology in healthcare provision [49]. Securing patient privacy, dealing with data security issues, and adhering to ethical standards all play a role in building trust in the relationship between patients and providers and in maintaining the quality of the healthcare delivery system [59].

Ethical aspects serve as a guide in the determination of patient rights, the promotion of transparency and accountability, and the maintenance of trust in healthcare interfaces. The awareness of ethical considerations in healthcare design is fundamental for interfaces to enhance patients' privacy by allowing access only to the necessary information, preventing unauthorized disclosure, and minimizing ethical risks related to the use of technology in patient care [46]. The HCI approach thus gives designers the tools and frameworks for aligning ethical considerations in healthcare design. HCD techniques embed user needs and acceptable preferences into the design process of healthcare technologies to keep ethical perceptions of the developed products intact in the context of illumination and clarification of ideas. Ethical principles that are incorporated in the design of healthcare interfaces ensure that patients' or users' rights are upheld, data security is maintained, and the interface adheres to ethics standards and the requirements of the regulatory body. Ethically designed healthcare systems promote patients' confidence, provide better patient care, and minimize ethical risks associated with improper use of technology in the healthcare sector [60]. Thanks to implementing ethical aspects, HCI follows a long-term positive trend of establishing interfaces that guarantee patients' welfare and ethics [50].

Example: The goal is to craft a telemedicine platform where patients can meet physicians using a distant communication channel. Some of the ethical problems that we need to consider when designing this platform include making sure that patient privacy is protected during consultation via telecommunication, obtaining informed consent from the patient regarding the collection and usage of their data, and implementing safety measures that prevent unauthorized access to patient's data [36].

HCI principles act as the touchpoints of the design process, ensuring the platform is autonomous in the patient, transparent, and ethical frameworks. This feature may allow patients to select the people they allow to access their health records and openly provide them with information on how their data will be used and protected [61]. Integrating ethical considerations into the design of the telemedicine platform will ensure that patient's rights are respected and that high standards of ethics are kept in the remote services delivery. In Table 4 below, Key ethical considerations in healthcare design in HCI.

Table 4. Key ethical considerations in healthcare design in HCI.

Ethical considerations	Description	References
Patient privacy and confidentiality	Preserving the patient's privacy and confidentiality in healthcare interaction and connected technologies.	[32,35]
Data security	Prescribing proper measures to control the information security issues that affect the patients' records indicating cases of unauthorized access, breach, and misuse.	[41,45,47]
Informed consent	Informed consent issues related to the use of health data from patients: the authorization for collection, use, and sharing of data.	[39,42]
transparency	Enshrining the principles of transparency in the design and subsequent functionality of health-care interfaces, inclusive of AI algorithms.	[45,46]
Equity and accessibility	Promoting accessible interfaces for healthcare where the technology appropriately accommodates the needs of any person with disabilities or from diverse backgrounds.	[46,50]
Accountability	Ensuring that technology is utilized responsibly within patients' care by creating accountabilities for designers, developers, and healthcare institutions.	[39,45]

3. Interface design in healthcare

3.1. Historical perspective on interface design in healthcare

Healthcare interface design has been deeply connected with technological developments; medical practices and the expectations of healthcare professionals and patients have progressed continuously. This history traces key milestones that have shaped the ever-changing landscape of interface design in healthcare. In this exploration, we see how innovation and necessity have driven design and technology to work together, improving accessibility, efficiency, and user-centricity over time [51,61].

3.1.1. Pioneering years

The roots of interface design in healthcare can be identified as far as the early years of computerization within healthcare settings during the mid-20th century. This immature stage saw the introduction of EHRs and moved slowly from paper-based systems. Early interface designs, including command line interfaces and rudimentary functionalities, marked the first steps to digitizing healthcare information. Nevertheless, their implementation could have been more cautious and characterized by technology limitations and resistance to moving away from standard manual processes [62].

3.1.2. Emergence of graphical user interfaces (GUIs)

The 1980s saw the transformation of the historical narrative with GUIs, inspired by personal computing innovations and bringing visual elements like icons, menus, and windows to the users' interaction with technology. This transition changed users' experience and set the stage for a broader adaptation of electronic interfaces in healthcare environments. Incorporating GUIs into EHR systems facilitated more straightforward navigation and data entry for healthcare professionals [53,54].

3.1.3. Rise of EHRs

In the late 20th century, there was a paradigm shift with the emergence of EHRs and their wide acceptance. These systems marked not only the centralization of patient information but also a new era of interface design concerned with interoperability, data accuracy, and accessibility. The challenge was making interfaces that catered to the varying requirements of health workers, from doctors to nurses and administrative officers. Usability was a key issue, and such an iterative design approach was adopted where interfaces were refined based on user feedback [49,63].

3.1.4. Mobile revolution and patient engagement

The dawn of the 21st century ushered in the mobile revolution, necessitating the evolution of healthcare interfaces to function with smartphones and tablets. Mobile health applications and patient portals became significant elements, taking medical connections beyond the walls of healthcare facilities. Interface design shifted toward increased patient engagement, aiming to develop user-friendly applications that empowered individuals to actively manage their health. The 20th century was a great transition, moving to inclusive design and considering that healthcare consumers were diverse in terms of health, race, gender, and more.

3.1.5. HCD principles

As interface design developed in healthcare, the involvement of HCD principles became paramount. The approach's focus changed from technologically centered solutions to user-oriented ones, focused on the needs, preferences, and workflows of healthcare professionals and patients. HCD introduced a comprehensive user perspective, where users were involved in the design process through usability testing, feedback sessions, and iterative refinements. This approach made interfaces more usable and, as a result, improved user satisfaction [24,64].

3.1.6. Integration of AI

The integration of AI has transformed the landscape of interface design in healthcare over the past few years. AI-enabled interfaces utilize machine learning algorithms to process massive datasets and give healthcare providers usable intelligence. Diagnostic interfaces, decision support systems, and chatbots have become essential features that make clinical workflows smoother, aiding healthcare providers in making decisions. The issue here is designing interfaces that make it easy for AI and human users to collaborate effortlessly while ensuring transparency, trust, and ethical use of AI in healthcare [19].

3.1.7. Telemedicine and virtual health interfaces

Telemedicine changed the global landscape dramatically and rapidly, facilitated by external events like the COVID-19 pandemic. Telemedicine interfaces became crucial pathways for virtual consultations, remote monitoring, and the delivery of digital health. The design challenge broadened to build interfaces that enabled efficient communication between healthcare providers and patients and maintained the human touch in distance interactions [65].

The historical perspective of interface design in healthcare reveals a story of constant progress and adjustment. Throughout the evolutionary pathway, from the simple interfaces provided by pioneers to current AI-based seamless interfaces, it is evident that this journey is relentless in improving the quality of patient care experiences and utilizing technology for healthcare delivery. This is predicted to be the future, where interfaces will have significant roles to play in integrating upcoming technologies, personalized medicine, and the constant search for integrated, seamless, patient-centric healthcare experiences. The developmental history of medical interface design stands as a monument to the persistence and creativity inherent in the constantly changing nexus between healthcare and technology. The below Figure 5 shows Process for integrated user interface design in Telemedicine and virtual health interfaces.
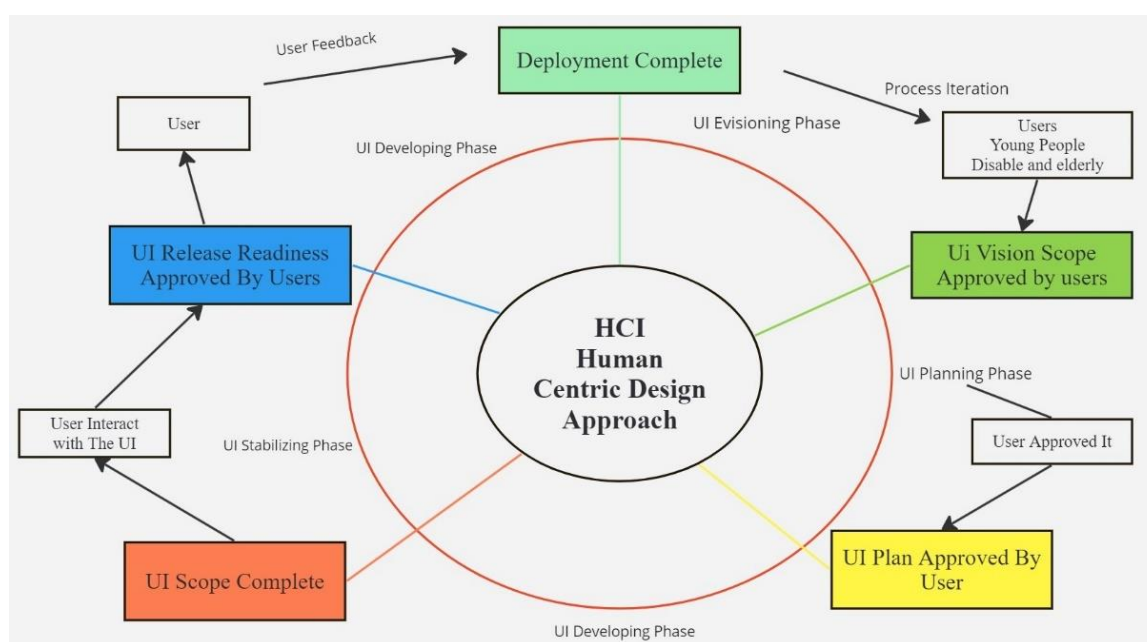

Figure 5. Process for integrated user interface design.

3.2. Challenges and limitations of existing interfaces

In the increasingly dynamic landscape of healthcare, interfaces are critical in defining medical systems' efficacy, convenience, and efficiency. However, these interfaces have their challenges and limitations. This section goes into an in-depth analysis of the intricacies associated with current interfaces available in healthcare facilities, providing valuable insights into the challenges for healthcare professionals, patients, and even system administrators. The difficulties regarding

healthcare interfaces are varied, such as those regarding interoperability to other issues, the security of data, and the fine line between innovation and usability. It is necessary to examine these challenges profoundly to see how we can progress further.

3.2.1. Interoperability issues

Despite the advancements in modern healthcare interfaces, interoperability is the biggest challenge of the growing integrated innovative features such as AI, machine learning, and IoT gadgets. The first problem is that different systems can no longer talk to each other, hence creating what can be described as stovepipe data flow, which complicates the overall care offered to patients. For instance, EHRs, which primarily aim to enhance the flow of healthcare information, are not interoperable with other health information systems, creating fragmented patient records that can endanger clinical choices. Also, practice-specific non-standard data formats and variations in data entry conventions contribute to this problem and consequently prevent the creation of a consistent, accurate, and productive view of patient data, which is critical for efficient healthcare delivery [32,34,66].

These are compounded by the emerging technologies that come with other complexities. For example, the combination of diagnostic tools based on artificial intelligence and machine learning algorithms involves data from several sources and often enters data-intensive types of data. However, in the absence of a common communication protocol for data sharing, these technologies may fail to extract, obtain, or analyze the relevant information, leading to their reduced efficiency and applicability. A cross-sectional study conducted by R. Mishra et al. [3] described an example of the deployment of an AI-oriented predictive analytics tool in a big healthcare network, which demonstrated critical issues with regard to data integration. According to the current tool, the data could be extracted from EHRs, imaging systems, and laboratory information systems. Nevertheless, the lack of specific common requirements for the integration of data sources resulted in delays in data availability and disagreement of the predictive performances, which resulted in a minimal clinical usefulness of the tool. Importantly, it raises the challenge of effective interoperability that will realize the potential of AI and machine learning in the health sector [67].

Solving these issues of interoperability requires an integration of standard data and architectures. Solutions such as the Fast Healthcare Interoperability Resources (FHIR) standard have been established to enable the integration of data across different healthcare systems. Some of the benefits of using FHIR include systems being able to communicate by using a common language instead of elaborate data conversion. Moreover, the application of blockchain technology enhances the sharing of information across various platforms, being highly secure and not able to be manipulated. Blockchain system creates an auditable record of patient history and preserves data integrity to promote a smooth exchange of healthcare information while using artificial intelligence and machine learning models that require constant updates and accurate data sets [68].

Cloud technologies also provide a feasible solution for the problems of interoperability since they can be used as a single data hub for information gathering and processing. Data gathered in multiple applications can be integrated into cloud-based healthcare platforms, increasing compatibility and making certain data available when required. For instance, a new application of a cloud-based EHR system in a multi-hospital network helped in sharing actual data and integrating different AI-based decision support tools, which led to at least a 20% decrease in diagnostic errors and better outcomes among patients (W. E. Macka et al.) [9]. To achieve this, significant steps have been made toward

utilizing cloud infrastructure to improve the systems' interchangeability and incorporation of other technologies that require extensive data accessibility.

Additionally, not only the problem of interoperability can be solved through technical means, but this issue also raises questions of an ethical nature, first of all concerning the protection of data. The introduction of AI and machine learning brings new risks since these tools need to be fed with patient information. Moreover, a proper approach to data sharing and the compliance of the data sharing procedures with particular guidelines, for example, the General Data Protection Regulation (GDPR) or The Health Insurance Portability and Accountability Act (HIPAA), is key to patient trust and data protection from unauthorized access or leakage. Data encryption n and accurate access control are the basic principles of secure data exchange, critical to working with AI in healthcare using ethical norms. W. E. Macka et al. [9] explained how the enhancement of end-to-end encryption and multi-factor authentication in the AI-enabled diagnostics system of a hospital reduced cases of unauthorized access, thus highlighting the need to enhance data security in the integration process.

One can agree with the idea that further enhancement of cooperation in the sphere of using new technologies in digital health greatly depends on the elimination of interoperability issues. Blockchain and cloud technologies, which are the most promising, should be adopted together with strict application of data security measures with the use of standardized data models that would prove efficient in the integration of the emerging technologies without posing threats to patient safety or data credibility [69]. To respond to these concerns, one will not only improve the healthcare delivery system but also continue the development of HCI in the healthcare industry for better patient care models.

3.2.2. Data security and privacy concerns

The transition that healthcare has been experiencing has made data confidentiality and security a major concern. As patient information, such as medical histories, diagnostic information, treatment plans, and details, are considered Protected Health Information (PHI) and are fairly securely stored, healthcare systems act as excellent targets for hackers. Patients' information can be leaked in these hacks, and this erodes the public's confidence in hospitals and other healthcare facilities that implement innovative digital health solutions. As the penetration of HCI technologies, including AI for diagnostics, telemedicine, and patient mobile applications, increases, risk profile changes and poses different challenges in data security that are a merge of technical and behavioral risks [70].

One major issue that is hard to tackle in relation to achieving healthcare data security is ensuring security and at the same time creating high usability—an essential area of HCI. These measures include the use of strong passwords, Multi-Factor Authentication (MFA), and constant updates to the system, which can be disruptive for the users, especially in acute care settings where time is of the essence. For instance, MFA is one of the most effective ways of defending information, but it may cause a lot of discomfort among clinicians, especially when they have to retrieve information from the patient's records during an emergency. To combat this, privacy and security concerns need to be fully incorporated into the healthcare systems, to become a "real" security measure by design for the HCI systems. It also ensures that security implementations do not negatively impact the ease of use of the healthcare interfaces, hence retaining the attention of clinicians toward addressing the patient's needs without neglecting security.

Innovations that can improve the security and privacy problems in HCI include blockchain technology. The use of blockchain offers an ideal solution when it comes to sharing data since each

transaction is encrypted and recorded across a distributed ledger, hence making it very hard for anyone to tamper with the data. Blockchain in healthcare, for instance, can be applied in the development of records that are personalized, open only to those people with access rights; records that could follow the patient around the care continuum without compromising their privacy but enhancing data sharing among institutions. For instance, a pilot study performed in a multi-hospital system showed that utilization of blockchain technology for EHRs significantly minimized the number of hacking attacks and unauthorized access to patient's data, thereby improving the security of data while at the same time making it easier for the healthcare providers to access important data of the patient at the right time. This shows how the existent emerging technology strategies can be adopted to deal with the challenges of data security in HCI healthcare information [71].

Still, technical approaches are insufficient; therefore, guidelines and procedures in organizations are also effective in protecting patient information. Quarterly security checkups, extensive working policies and procedures, and proper reminding of policies are critically important in raising the organizational security consciousness among healthcare organizations. For instance, W. E. Macka et al. [9] pointed out that organizations that conducted security audits regularly and provided healthcare facility staff with training on the best practices of handling patient data experienced a 30% reduction in their security threats [21,72]. Given the fact that threats can emerge at any time throughout the day, training that focuses on the need to ensure data security in relation to the clinical activities of the healthcare worker prepares the latter to identify and address these threats appropriately. Furthermore, while dealing with large sums of patient data, healthcare organizations need to have proper measures and guidelines on how to address such issues as data breaches and what measures should be taken as soon as such incident happens.

Technical and organizational controls are not enough; data privacy has other ethical dimensions that include the requirement for the protection of patient information. Since the emergence of advanced technologies in HCI within the field of medicine, many AI algorithms deal with a vast amount of patient data, questions regarding the ownership of data, and patients' consent. The principle of informed consent and patient autonomy should be applied to update patients with information on the use of their data, access thereof, and its protection [73]. For that reason, concerns arise regarding the ethical issues of AI in predictive analytics in clinical decision-making contexts. Explanatory and fair AI frameworks are an important component that can help make sure that those technologies do not violate patients' rights and do not embed bias in care.

In addition, novel techniques like differential privacy and federated learning are starting to be seen as useful approaches for the protection of patient information and for the further development of AI in healthcare. Differential privacy puts noise in the data so that no single data point will point back to a particular patient; federated learning enables AI models to be trained using data at one location or another without ever congregating the data. Besides, these approaches not only aim to protect patient's privacy but also benefit the AI models' stability and effectiveness, which contributes to a safer and more suitable HCI system in healthcare.

3.2.3. Usability and user experience challenges

Usability holds a place of great importance in the context of interface design regardless of the field. However, in healthcare, it could not be as important as it is now since the consequences of a mistake are very high. Issues with usability are problematic not only for healthcare workers but also for patients. Due to the intricate subject matter and diverse target audience, simplicity, ease of use, and

adaptability are required to implement functionalities based on the population [56]. Health professionals, in particular, work under high time pressure; the interfaces that are supposed to support them should not instead challenge them. Inefficient interfaces can result in wasted time, an extra mental load that the user has to process, and the possibility of data input or data recall errors, which could become fatal. Similarly, patients who are using patient portals or mobile health applications require an interface that allows the patient to remain an active participant in the process of their treatment. To overcome these challenges, some options are possible as follows. One strategy that can be employed is the UCD, which involves the users in the development and, especially, the evaluation processes [71]. If designers are to integrate the expectations of both healthcare workers and patients, the interfaces created will be more prepared to meet their expectations and thus increase usability and decrease the occurrence of errors. Also, dynamic interfaces that change depending on the user's performance and options chosen will also improve its usage. For instance, interfaces could present a basic version to beginners and a detailed version to expert users. Furthermore, the inclusion of AI within the analytics can assist with rendering real-time usability problems and constantly evolve; it could also reduce the degrees of freedom that are present in any cognitive system and therefore the overall cognitive load while enhancing the overall effectiveness of the process and work flow. In addition, context-aware systems that are adapted to the user's environment could reduce interference possibilities and even improve usability [72,73].

In the patient context, more could be achieved by enabling them to personalize the interface according to the user's specific trends and conditions. This could incorporate a subject-specific control panel, a presentation of the most used options, and single-click routes of a user profile typified by patients. Another advantage can also be achieved through the application of natural language processing (NLP) tools to ease the process and enable users to type in commands or conversational interfaces to enhance accessibility and enjoyment [20,24].

3.2.4. Integration of emerging technologies

The use of newer technologies like AI and machine learning could transform healthcare, but this also comes with several challenges. To support advanced technologies in healthcare, interfaces must be designed in such a way that these changes do not interfere with the current interfaces in the organization. These technologies must not act as barriers to increasing the efficiency of healthcare systems. Interfacing of systems needs to capture the complexities of AI-based systems without burdening healthcare professionals. Furthermore, the inclusion of AI in human–computer interfaces in healthcare has caused several ethical issues. When decision support systems are based on AI, one must carefully incorporate the level of independence of the decision-making process between two inputs of an expert system and a healthcare specialist [1,22]. This calls for communication and interaction between AI systems and human beings, as well as enabling users to understand the processes that were followed to come up with certain decisions. For instance, AI interfaces should contain elaborate descriptions of the algorithm's recommendations, so that healthcare professionals can trust the result. This openness is important for preserving the healthcare delivery process as well as for the safety of the patients [22,68].

Several key tools could help to overcome these challenges. One is to build systems where AI capabilities and decision-making are integrated with human knowledge. Such systems can be designed to give American clients AI-based advice in a way that enables healthcare professionals to think and

act clinically. However, implementing AI in interfaces should also include steps on how to conduct testing and validation to conform to clinical and ethical requirements. This ranges from proper risk analysis and ensuring that appropriate measures are put in place to help avoid compromising the quality of medical treatment. AI interfaces should also be designed with global usability and accessibility [55]. This can be achieved through easy-to-understand dashboards that display the data generated by AI, so that decisions can be made promptly by the medical practitioners [74]. Healthcare consumers should also be included in training and education programs for healthcare providers on how to use AI tools to improve their comfort and competence with the new technologies. Another important factor is the maintenance of AI systems to conform to current clinical standards and prevailing or emerging ethical regulations. This process is continuous and entails the assimilation of feedback cues in the hub to facilitate constant modification of the environment depending on feedback received from users and their performances [61,73].

3.2.5. Resistance to change and training

The healthcare sector, a field considered to be conservative, can often be seen as reluctant to implement new technologies and interfaces. This resistance stems from people becoming used to certain ways and structures that are already in place, for instance, legacy systems within healthcare providers. Loyalty and familiarity to these systems make it hard for these professionals to evolve, even though new interfaces come with advanced functionality and comfort. This resistance is not just an unwillingness to change; the implementation of new systems may be challenging in this respect, training becomes imperative for the acceptance of new interfaces [74]. However, learning must be complemented by change management and the engagement of healthcare professionals from the time when training is being developed. This involvement can aid in decreasing resistance by increasing the likelihood that the new systems reflect the expected job requirements of users [11,12].

Another important dimension of managing resistance is designing interfaces that will enable an easy shift. It must be as easy to use as possible and not affect any existing process in a way that requires reworking. A possibility is the gradual introduction of new interfaces while simultaneously preserving the interaction with existing ones already known by healthcare providers. Such a phased approach can help reduce the steep learning curve and the difficulty people face while transitioning, while continued support and training help beyond the training sessions. This may include online training sessions, support, and quick "patches" to correct any problems that may emerge as healthcare organization of security and co-operation in Europe (OSCE) users start using the new interface. This kind of support may facilitate the transition process, and any complications that arise can be solved in the shortest time possible [17].

Interface designers should retain some of the looks and appearance of the older interface. This way, healthcare workers can slowly adapt to the new system using their prior knowledge and experience and periodically face new aspects of the system. User feedback should also be incorporated in periodic updates. Finally, user interfaces should be simplified to deliver the best functionality while allowing an easy and manageable change for the healthcare authorities. Therefore, by handling resistance issues and ensuring that favorable and comprehensive training and support are extended, the health facility will be in a better position to adopt new technological features [8,75].

3.2.6. Resource constraints and infrastructure challenges

In many healthcare systems, there are unfavorable conditions of scarcity of resources and lack of infrastructure. These can be big challenges for the application of modern interfaces. The adoption and implementation of modern interface technologies, especially web-based technologies, usually require considerable amounts of money; this may be a major problem in small health facilities where funds are scarce. These financial limitations limit the ability of these facilities to improve on the existing systems and implement new interface technologies. Resource scarcity is compounded by inadequate infrastructure, which is evidenced by outdated hardware, inadequate transmission capacity of networks, and the lack of broadband connectivity. Such problems can be common in rural hospitals without the resources to implement well-designed interfaces [22,45].

Solving these challenges can only be achieved through an extended strategy for the improvement of the current infrastructure or through the enhancement of precise and cheap interfaces that can be adapted to specific healthcare requirements and capabilities. For example, cloud-based interfaces could present a real solution, as local on-site equipment is expensive and there are issues related to the flexibility of data access and storage. Also, interactions between healthcare professionals, the government, and technology suppliers could help to distribute resources and deploy proper infrastructures. The digital divide concerns the differences in the use of new technologies and the internet, especially between urban or economically well-developed areas compared with rural areas or those that are not economically endowed [76]. Filling this gap is crucial so that all healthcare facilities have access to interface technology developments. Such initiatives include government promotion of global broadband internet and funding programs in facilities that may not be so endowed. Thus, promoting equity must also address innovative financing models. Such models could be public private partnership (PPPs), funds, or concessionary loans for the improvement of health facilities. Such initiatives can assist in leveling out the "field externalities" so that it becomes possible for every healthcare provider to incorporate the technologies that are most advantageous and reap the appropriate advantages [43,48].

Furthermore, interfaces should be made relatively flexible to operate in different infrastructure settings. This includes making interfaces that match low-bandwidth environments or even interfaces that can run on low-end computing devices. Thus, when implementing new technologies, the healthcare industry must be prepared for different levels of development and resource provision [77].

3.3. Need for user-centric design in healthcare systems

In the complex world of healthcare systems, the call for user-centric design is a transformative necessity. The interface landscape in healthcare is a meeting point of technology and the human touch, requiring designs that consider users' requirements, experiences, and well-being. This section thoroughly investigates the necessity for user-centered design in healthcare systems, discussing how this could influence patient care and health professionals and create a holistic approach to medical processes [7,12]. The human–computer interaction is depicted in Figure 2. The below Figure 6 shows the features of HCI.
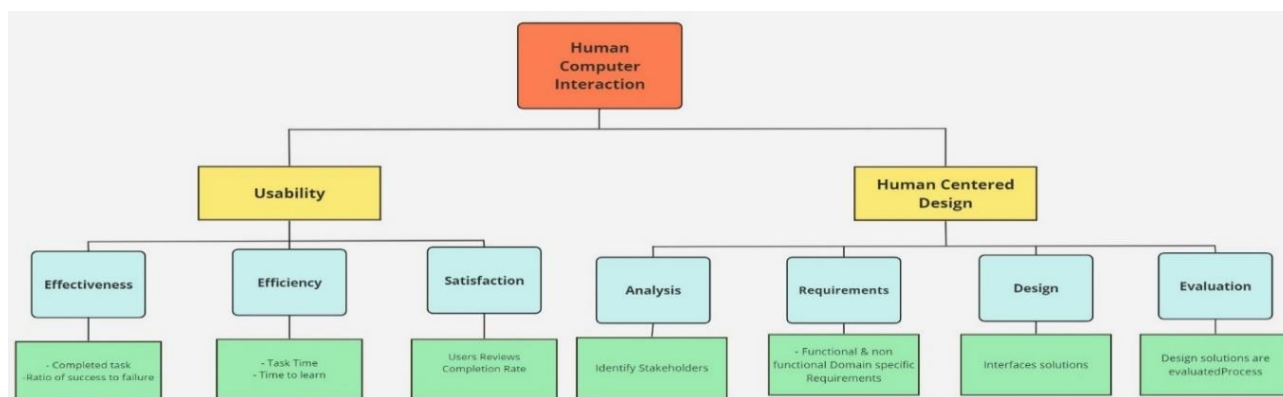
Figure 6. Human–computer interaction.

3.3.1. Elevating patient engagement and empowerment

User-centric design in healthcare aims to enhance patient engagement and empowerment at its core. Patients are not just passive healthcare recipients; they assume an active role in their journey to well-being. User-centric interfaces are presented through patient portals, mobile health applications, and telemedicine platforms that enable patients to use their data, make appointments for themselves, and be involved in the work of healthcare providers. Healthcare systems require user-centric design, especially regarding the possibility of boosting health literacy among patients. Intuitive interfaces with precise information, educational resources, and interactive features help to make informed decisions. This helps instill a vital sense of agency among patients and change them from passive care recipients into knowledgeable stakeholders in the healthcare process [19,78].

3.3.2. Streamlining healthcare workflows for professionals

Healthcare professionals working under the pressures of complexity and high-stakes environments stand to benefit significantly from user-centric design. Building interfaces adapted to the specific work routines of physicians, nurses, and administrative personnel can simplify processes, decrease mental strain, and prevent errors. The need is to create interfaces that fit perfectly with the natural beats of healthcare workflows to increase productivity and enable professionals to concentrate more on patient care [79]. Consider the place of EHRs; they are a central part of healthcare interfaces. User-centered EHR designs incorporate healthcare professionals' needs by reducing data input work burdens, promoting intuitive navigation, and offering intelligent decision support. Moreover, such interfaces become great tools that help doctors by complementing their knowledge and creating a more pleasant and efficient workspace [47].

3.3.3. Fostering collaboration and communication

User-centric design acts as a catalyst in driving collaboration and communication within the healthcare ecosystem. Cohesive and patient-centered care is facilitated through interfaces that enable easy information exchange among healthcare professionals, specialists, and support staff. Effective communication is of particular significance in a multidisciplinary healthcare environment where

various professionals work together to achieve holistic care. Take into account the collaborative nature of a healthcare team, made up of physicians, nurses, pharmacists, and other professionals. User-centric interfaces with functionalities such as secure messaging, shared calendars, and collaborative documentation help break down these silos and foster interdisciplinary communication [3,34].

3.3.4. Adapting to the evolving landscape of tele-health

The growth of tele-health has put greater emphasis on user-centric design in healthcare systems. Virtual consultations and remote healthcare delivery interfaces, which serve as the conduits for telemedicine, need designs that focus on ease of use and patient friendliness. The difficulty is in recreating the intricacies of face-to-face interactions through digital platforms, creating an emotional bond between healthcare providers and patients. This issue is addressed by user-centric telehealth interfaces that include video conferencing, secure messaging, and interactive tools for remote examinations. These interfaces are meant not only to close the physical gap between providers and patients but also to recreate the empathy and personalized nature of care that characterizes standard healthcare encounters [5].

4. Importance of interactive interfaces for medical professionals

4.1. Enhancing efficiency in clinical workflows

In the complex fabric of healthcare, where every moment counts and decisions are critical, clinical workflows are crucial to securing optimal delivery of patient care. In this rapidly changing and stormy field, carefully designed interactive interfaces for medical professionals are indispensable aids. Their purpose is to facilitate, empower, and elevate the complex work of clinical workflows. This section investigates the diverse and complex significance of interactive interfaces within the healthcare environment. We focus on the interventions made by these interfaces, amplifying efficiency, reducing cognitive burdens, and creating seamless collaboration within clinical workflows [80]. Nevertheless, as we explore contemporary healthcare, interactive interfaces are no longer merely add-ons to transplants for efficient and patient-centric healthcare delivery but an influential driving factor at its heart [47].

4.1.1. Streamlining information access and retrieval

Seamless access and retrieval of critical information are among the main contributions of interactive interfaces to clinical workflows. Medical personnel often have to deal with large databases, patient records, and diagnostic reports in a healthcare environment. Interactive interfaces designed with user-centric principles enable intuitive navigation and intelligent search functionalities that help clinicians access the necessary information promptly. Consider EHRs, one of the pillars of healthcare interfaces. User-friendly interfaces foster efficiency because patient-related information is presented in a structured and easy-to-access manner. Customizable dashboards and instant search options with summarized patient timelines reduce the time spent looking for information and allow medical professionals to make quick decisions [81].

4.1.2. Facilitating decision support

Some interactive interfaces equipped with decision support functionalities act as great companions for medical professionals during decision-making. These interfaces use sophisticated technologies such as artificial intelligence and machine learning to process data and generate real-time insights. Decision support tools help clinicians interpret complicated medical information, detect patterns, and make evidence-based decisions. Consider a diagnostic interface that combines AI algorithms to help radiologists interpret medical images. Such interfaces make the diagnostic process faster but also increase accuracy and consistency. These interfaces function as collaborating agents where a medical practitioner is presented with relevant information and possible diagnoses, enhancing their capability to make various decisions [49].

4.1.3. Integrating task automation

The automation of tasks through interactive interfaces significantly enhances efficiency in clinical workflows. Automating repetitive and time-consuming tasks, such as data entry and administrative processes, can free medical professionals to focus on patient care and complex decision-making. For instance, interactive interfaces in systems can automate many mundane documentation tasks so that the clinician is freed up to spend more time interacting with patients. In addition to speeding up workflows, automation also reduces the chance of errors that come with manual data input, thereby increasing overall efficiency in healthcare delivery [17,50]. The below Figure 7 shows the Improving communication and collaboration in HCI.
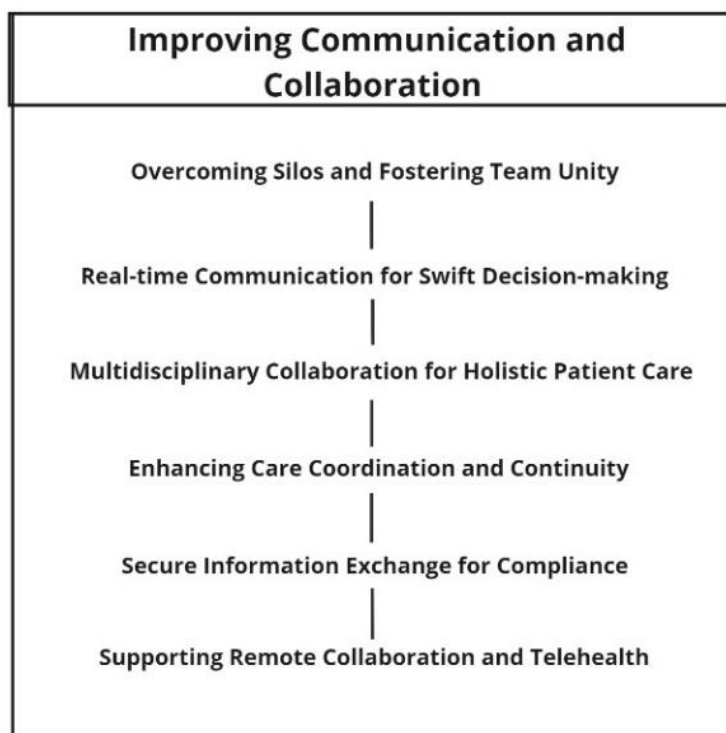

Figure 7. Improving communication and collaboration.

4.1.4. Enhancing communication and collaboration

Good communication and teamwork among health professionals are essential for holistic patient care. Interactive interfaces enable accessible communication through secure messaging, shared calendars, and collaborative documentation. These functionalities close the communication gaps within a multidisciplinary healthcare team. Think of a collaborative healthcare platform where medical professionals from various branches could gain access to a familiar interface. It supports real-time communication and makes it possible to collaborate in decision-making. Interactive interfaces developed to improve teamwork help create a harmonious healthcare environment where professionals can share pertinent information and perspectives [37,59].

4.1.5. Improving mobile accessibility

The flexibility of the interactive interfaces is also stressed due to their adaptability to mobile platforms that allow healthcare professionals easy access to essential information anytime and anywhere. Mobile interfaces enable clinicians to access patient data, review inquiries, and coordinate care anywhere, but they also increase the flexibility and responsiveness of clinical workflows [47]. For example, a mobile application allows physicians to access patient records and update information while moving between different units or locations in a healthcare setting. This movement saves time and ensures that medical professionals can make their decisions promptly without being restricted by physical obstacles [57].

4.1.6. Enabling data visualization for insights

Interactive interfaces are also essential in translating complicated medical data into visually comprehensible insights. Tools for data visualization within these interfaces display information in a format that is easy to understand, thus enabling medical professionals to quickly identify trends, patterns, and outliers associated with patient data. Take a population health management system data visualization interface. It could be an interactive dashboard with important health indicators, disease prevalence rates, and results of treatments. Such visual representations allow healthcare professionals to notice population health trends, allocate resources efficiently, and make knowledgeable decisions benefitting the overall patient results [16,36].

4.1.7. Supporting continuous learning

In a dynamically developing medical field, lifelong learning is vital for healthcare professionals to be aware of recent innovations and practical approaches. Interactive interfaces can play a significant role in enabling ongoing education by granting access to educational materials, training modules, and real-time updates about medical research. For instance, an interface in a medical education platform can provide interactive modules, virtual simulations, and access to a repository of peer-reviewed articles. With built-in learning resources directly into the interface, medical professionals can increase their knowledge and skills without disrupting their clinical workflow [60].

4.2. Improving communication and collaboration among healthcare professionals

Effective communication and smooth collaboration between healthcare professionals are the critical linchpins within the complex fabric of healthcare to provide comprehensive patient-centered care. This section discusses the pivotal role of interactive interfaces in facilitating effective communication and collaboration among healthcare professionals [11]. These interfaces can serve as catalysts for raising the synergistic quality of healthcare teams by overcoming gaps and promoting real-time communications and collaborative platforms.

4.2.1.   Overcoming silos and fostering team unity

Interactive interfaces act as the missing links that join these silos together, also creating unity among team members. By offering a common place where information can change hands, healthcare professionals from different fields may collaborate effortlessly, removing obstacles that impede communication. Imagine a collaborative healthcare platform where physicians, nurses, specialists, and administrative staff join together through one interface. This ensures a smooth flow of essential patient information and fosters a comprehensive view of a patient's health journey. This ultimately leads to a more interrelated and cohesive healthcare group striving toward comprehensive patient care [59,61].

4.2.2.   Real-time communication for swift decision-making

In healthcare, where things are constantly changing, quick decisions often matter. Interactive interfaces enable real-time dialogue, implying that healthcare professionals can share information, discuss cases, and make decisions on time. Secure messaging, shared calendars, and virtual collaboration tools allow professionals to stay in touch no matter where they are. For instance, an integrated secure messaging system in the healthcare interface will enable surgeons and anesthesiologists to share vital details about a patient's state instantly. This real-time communication speeds up decision-making and leads to a more agile and responsive healthcare ecosystem [16,36].

4.2.3.   Multidisciplinary collaboration for holistic patient care

Healthcare is an inherently multidisciplinary field in which professionals contribute their expertise to ensure quality patient care. Interactive interfaces offer platforms where professionals from various fields can work effectively by sharing insights, treatment plans, and progress updates. This interdisciplinary collaboration is especially significant in such complex cases that need to engage several specialties. The interface combines diagnostic images, pathology reports, and similar treatment plans that create a holistic conversation, leading to an integrated and informed approach to caring for patients [11].

4.2.4.   Enhancing care coordination and continuity

Care coordination is essential to successful healthcare delivery in cases where the patient requires long-term treatments, chronic diseases, or transfers between different care sites. These interactive interfaces facilitate easy care coordination by providing a single point where participants can access

and modify or maintain patient information. This ensures continuity of care, minimizing chances of errors, hence improving the patient experience in general. Consider an EHR system feature that allows viewing a patient's care plan, medications taken, and recent laboratory results. Such information is available to all care team members, ensuring coordinated practice and avoiding fragmented care [61].

4.2.5. Secure information exchange for compliance

Secure information exchange is paramount in the era of strict privacy regulations. Interactive interfaces protect the privacy and confidentiality of patient data, thereby adhering to the standards established by acts such as the Health Insurance Portability and Accountability Act (HIPAA). These interfaces provide encrypted communication channels and access controls, thus offering a secure platform where healthcare professionals can exchange sensitive information. For instance, a safe document-sharing component within an interface enables radiologists to share comprehensive imaging reports with referring physicians. This provides an efficient means of communication and also ensures the protection of sensitive patient information during the collaboration process [57].

4.2.6. Supporting remote collaboration and tele-health

Interactive interfaces have helped the evolution of tele-health and remote collaboration. These interfaces go beyond standard healthcare environments, allowing professionals to liaise from a distance and tele-consult virtually. This is very useful where it is not possible or practical to be physically present. Take a tele-health interface wherein a primary care provider (PCP) collaborates with a specialist in real-time during virtual consultation [5,6]. The interface includes video conferencing, secure messaging, and shared documentation to simulate the collaborative aspects of a face-to-face consultation, with this flexibility in collaboration accessing expertise, whether remotely or in underserved areas [16].

4.3. Reducing cognitive load and decision fatigue

In the fast-paced and high-stakes world of healthcare, where each choice matters, decreasing cognitive load and combating decision fatigue are pivotal requirements. Most importantly, interactive systems developed for healthcare professionals become vital allies in this battle by providing tools and functionalities to help with the information processing process, improve cognitive performance, and facilitate better decision-making [40]. This part highlights how interactive interfaces have made such a massive change in the healthcare field by pointing out that they efficiently save cognitive load and free people from decision fatigue. These interfaces' innovative design principles and intelligent features make them catalysts for cognitive resource optimization among healthcare professionals, improving service delivery quality [54].

4.3.1. Streamlining information presentation

Cognitive load is caused by the vast amount of information that healthcare providers must process daily. To solve this problem, interactive interfaces use user-centered design principles to simplify information presentation. Intuitive dashboards, customizable views, and prioritized content mean that

these interfaces present the necessary information, requiring reduced cognitive effort related to data interpretation. Let us assume a clinician who uses an interactive interface to log on to their patient's Rather than searching through pages upon pages of textual data, the interface uses visualizations like timelines and graphs to showcase relevant health indicators and trends. This pictorial representation makes understanding more manageable and reduces the burden of cognitive load involved in managing large volumes of clinical data [62,63].

4.3.2. Intelligent decision support systems

Intelligent decision support systems and interactive interfaces help healthcare professionals manage complicated medical situations. These systems incorporate artificial intelligence and machine learning algorithms to process data, recognize trends, and provide immediate information. This proactive support reduces cognitive load and complex decision-making, especially in cases of numerous variables. For example, an interactive diagnostic interface may employ machine learning to process medical imaging information. The interface helps radiologists pinpoint possible anomalies, provide differential diagnoses, and provide relevant clinical evidence. By supporting decision-making with intelligent inflections, these interfaces allow healthcare providers to act more efficiently and reduce mental effort [46]. The impact of interactive interfaces on clinical workflow is depicted in Figure 3.

4.3.3. Personalized dashboards and workflows

Each healthcare professional has unique preferences and workflows. Interactive interfaces aware of differentiation recognize this heterogeneity and provide individualized dashboards and workflows. These interfaces reduce the cognitive load of navigating irrelevant information and features because they enable customization according to roles, responsibilities, and personal preferences. Take, for instance, an interactive interface used by a nurse in a hospital environment. The interface can be customized to focus on tasks like medication, vital sign recording, and patient assessments. This individualized method facilitates streamlined workflows and allows the nurse's cognitive resources to be devoted exclusively to tasks that correspond with their specific roles, thereby maximizing efficiency [60].

4.3.4. Context-aware alerts and notifications

Prompt and situation-sensitive alarms are essential in lowering the cognitive workload by guiding attention to important information. These interactive interfaces involve clever, alert mechanisms that consider the context of the healthcare professional's tasks and generate relevant notifications. These interfaces minimize undue interruptions and deliver information promptly, thereby eliminating the case of decision fatigue associated with an overload of information. For instance, a clinician prescribing medications using an interactive clinical decision support system may be alerted in real-time about possible drug interactions. The system factors in the patient's medical history and current prescription, making the alert relevant to the chosen clinical situation. This focused approach optimizes alert effectiveness and relieves cognitive burden [61].

4.3.5. Integrating predictive analytics

The predictive analytics embedded in the interactive interfaces also reduce cognitive burden by informing on future occurrences and patterns. These analytics interpret historical data to predict probable outcomes, after which healthcare practitioners can make better decisions. Through predictions and recommendations, these interfaces help professionals influence issues before they get too serious. A predictive analytics-based interactive interface in a critical care environment that can forecast the chances of patient degradation can be used as an example. For example, the interface could underscore higher-risk patients using historical data, enabling healthcare professionals to plan resources and intervene where necessary. This foresight helps early intervention and eliminates the stress that comes with permanent vigilance [60].

4.3.6. Integration of NLP

NLP within interactive interfaces significantly reduces cognitive load, especially in tasks involving documentation and data entry. NLP allows interfaces to understand and process human languages, making voice-to-text features possible and reducing the need for complex information input. This speeds up tasks and reduces the cognitive strains attached to manual data entry. For example, a physician dictating clinical notes into an interactive EHR interface can use NLP to translate spoken words into text. This removes the requirement of manual typing so that the physician can concentrate on articulating complicated medical information without being burdened by processing data entry-related cognitive tasks [39]. The below Figure 8 shows the Impact of interactive interfaces on clinical workflows under the NLP.
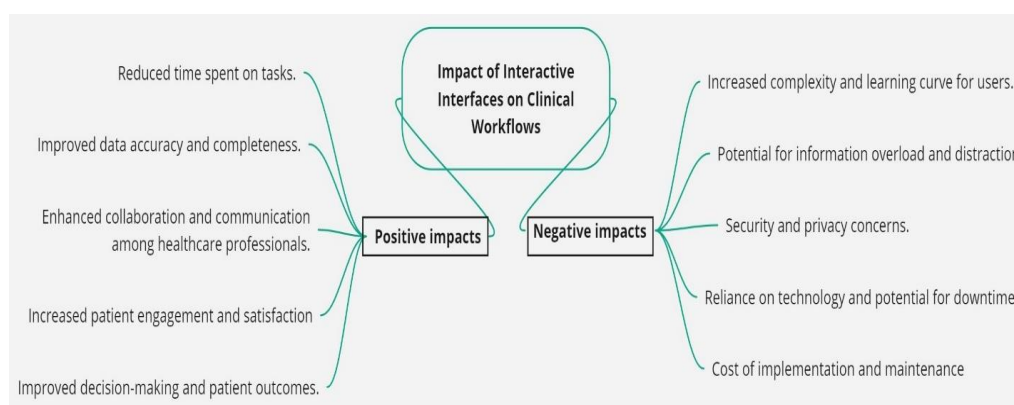

Figure 8. Impact of interactive interfaces on clinical workflows.

5. Design considerations for healthcare interactive interfaces

5.1. User-centered design principles

Interactive interfaces in healthcare require a detailed and user-focused approach to achieve usability and support positive interactions. The user-centered design help provide a basic framework for designing interfaces suited explicitly for healthcare professionals and patients. In this chapter, we

will focus on the major principles of user-centered design, discuss their importance, and offer illustrative cases of how they are used to navigate the complex terrain of healthcare interactive interfaces [10,12]. User-driven concept development is based on deeply understanding users' needs, likes, and problems. In healthcare, this means understanding the mindset and expectations of nurses, doctors, and patients. Using different methodologies that include user research, interviews, and observational studies is essential to know daily practices, pain areas, and ambitions. Example: A more holistic approach to understanding requirements might include shadowing healthcare practitioners during their day-to-day activities, through which designers could observe the tasks they perform, what information is essential to them, and the finer details of their decision-making processes [12].

Patient engagement is not just a tick but an essential aspect of healthcare interfaces. Designers need to acknowledge a wide range of patients' expectations, including accessibility and inclusiveness in interfaces that allow for patient management of their information. The goal is to involve the patients in their healthcare journey and decision-making process. Example: The scope of a patient portal can also extend to more advanced features like personal health records, interactive educative content, and scheduling appointments. This means that patients become active agents rather than passive recipients of the given care plans [64,65].

The practice of healthcare takes place in dynamic and frequently time-sensitive environments. User-centered design aims to design interfaces that fit into existing work practices with minimal cognitive effort, thus generating efficiency. Interfaces should be facilitators, not obstacles, to ensure that medical professionals can care for their patients without fighting interacting with technology. Example: The design of an EHR system should enable efficient input and retrieval of patient information in a fast, easy, and relevant context to clinical workflows [66]. Design with the user at its center is an endless process of improvement. This process involves the implementation of periodic feedback mechanisms.

Seeking user feedback in various design stages and incorporating it through iterative cycles can help improve interfaces to match the users' expectations. Successive usability testing sessions, such as those in which healthcare professionals participate, may target improving individual interface components by making adjustments based on user statements about directions, clarity of information, and overall satisfaction [67,68]. User-centered design principles further ensure that healthcare interfaces are usable by people of differing abilities and requirements. Observing accessibility standards is very important in designing interfaces that are inclusive of all people regardless of physical or cognitive disabilities. Example: A healthcare application that supports text-to-speech function, adjustable font size, and high contrast provides a higher accessibility level as it is more user-friendly for visually impaired people [59,70].

Consistency of design elements and interactions from one part of the interface to another, as well as in other healthcare applications, is not a purely aesthetic issue but represents one, if not the most important, pillar of user-centered design. Standardizing design elements helps to mitigate the learning curve, establishes familiarity, and improves overall usability. Example: The persistent placement of navigation menus, the everyday use of vocabulary terms, and coherent color usage make for a smooth user interface with reduced burden on users [71,72]. Validation with the natural world completes user-centered design. Usability testing in the healthcare environment helps to identify existing problems and potential opportunities for improvement. The effectiveness and responsiveness of the interface can, therefore, be tested while working in the environments that will use it. Example: Usability testing of the mobile healthcare application may involve healthcare professionals using it in

a simulated clinical environment, identifying potential usability issues associated with real-world usage, and suggesting necessary adjustments.

Table 5. Comparative analysis of successful and unsuccessful implementations in healthcare interface design.

Sr. No.	Criteria	Successful implementation	Unsuccessful implementation	References
1	User engagement	High levels of user engagement due to intuitive design and customization options.	Low user engagement is attributed to a complex interface and limited user training.	[15,35,36]
2	Workflow integration	Seamless integration into existing workflows, improving efficiency.	Disruptive implementation, causing workflow bottlenecks and resistance from users.	[23,37]
3	Training and support	Comprehensive training programs and ongoing support, minimizing user frustration.	Insufficient training resources lead to user frustration and suboptimal adoption.	[10,38]
4	Adaptability	Adaptable to evolving user needs and technological advancements.	Lack of adaptability, struggling to meet changing requirements and user expectations.	[39–41]
5	Data security and privacy	Robust security measures, ensuring data integrity and compliance.	Security vulnerabilities, compromising data integrity, and raising privacy concerns.	[42–44]
6	User feedback integration	Regular feedback loops are incorporated for continuous improvement.	Limited user feedback integration, resulting in unresolved issues and dissatisfaction.	[30,45]
7	Scalability	Scalable architecture allows expansion without performance issues.	Inability to scale, leading to system crashes and performance degradation under load.	[46,47]
8	Cost-effectiveness	Cost-effective implementation with a positive return on investment.	High implementation costs without clear benefits, lead to financial strain.	[8,48,49]
9	Alignment with goals	Aligns with organizational goals, contributing to improved patient outcomes.	Misalignment with organizational objectives, hindering overall healthcare delivery.	[49,50,73]

To summarize, user-centered principles lie at the foundation of healthcare interactive interface creation. Placing users first in the design process is instrumental for designers as they develop interfaces that improve efficiency and feasibility and lead to beneficial results [64,73]. This thoughtful approach to implementing these ideas guarantees that healthcare interfaces correspond to health

workers' and patients' requirements and contexts, creating a mutually beneficial relationship between technology and medicinal delivery [72,79]. In Table 5 below, shows the Comparative analysis of successful and unsuccessful implementations in healthcare interface design.

6. Future trends, challenges, and opportunities in HCI for healthcare

Wearable devices, IoT gadgets, and several other in-development technologies will greatly transform HCI in healthcare settings. These technologies not only develop but also radically change the way in which patients and care providers deal with the healthcare systems. Smartwatches, fitness trackers, and even specialized diagnostics in clothing result in several essential parameters being monitored at all times. Information from the devices can be easily communicated to the healthcare professionals in real-time and due interventions can be promptly made. However, this transformative potential comes with excellent challenges, especially in the realm of data privacy, security, and constant surveillance. Extending IoT into healthcare interfaces takes this a step further, combined with the increasing use of interfaces in healthcare applications and systems, which will also help in the connectivity of the various interfaces to create a network whereby devices, applications, and health systems can all work together to bring change to the patient's experience. Smart pills employed to check the patient's compliance with medications and connected inhalers as tools for asthma treatment are to be regarded as the next step in patient-centric medicine. These innovations create new avenues in healthcare with prospects for synergy between technologist clinicians and ethicists. All these elements point to the fact that clinical informatics is best implemented through collaboration to ensure the design and deployment of these technologies match the clinical needs and patient's rights and privacy.

Ethical concerns and patient privacy remain very important factors that need to be addressed every time we develop and deploy interfaces in the context of healthcare. Due to the enormous amount of data being generated from wearables and IoT systems, there are a lot of privacy concerns, who has access to this data, and how this data is used. The latest research reveals that there is a demand for better protective mechanisms to ensure the confidentiality of health information; it will be imperative to strike a balance between inventive and moral measures in emerging excellent, bulk, and patient-heavy HCI. For example, the advantages of using AI systems in identifying patterns, accuracy, efficiency, completeness, fullness, and speed of diagnosis treatment come with the black box problem of clinical decision-making ethics. These challenges are well addressed through interdisciplinary collaboration. The main way of integrating healthcare innovation with HCI is to create a multi-disciplinary team that comprises experts in healthcare, technology, ethics, and law to set out guidelines. This is not about simply incorporating the technology into the healthcare sector but also redesigning how healthcare is to be delivered. For instance, creating layouts that are easy to use by both the healthcare provider and the receiver of the healthcare requires work from the clinicians, patients, and usability and user-interface designers. This approach guarantees that technology improves the overall experience of receiving healthcare services.

Healthcare interfaces as a merge of wearable technology and IoT means a revolutionary shift in patient management by introducing timely and personal-specific approaches. For instance, it is possible to wear Electrocardiogram (ECG) monitors that can identify abnormal heartbeat and notify the healthcare givers before a life-threatening event happens. These are not merely technological enhancements but very profound changes in the clinical model. These technologies have the added effect of giving rise to new forms of care delivery, including remote care and telemedicine, which are

extremely effective in remote geographical areas and for those who are not well-endowed. However, the adoption of these technologies is not without certain difficulties, as this review seeks to find out. One of these is the digital gap between those who can use modern digital technologies and those who can only dream of possessing such technologies. This increases the gap between rich and poor people regarding health, especially in weak market areas that may not have efficient internet technologies or gorger devices. For all patients to gain access to these technologies, measures are required to square these disparities, such as making sure that interfaces are available across different devices and do not require high bandwidth connections. Another highly relevant operation challenge is the resistance to change within the healthcare setting. Healthcare delivery has been slow in adopting change, namely in applying new technologies that are introduced in practice settings. These four challenges imply that, to address this resistance, one has to focus not only on the training programs but also on the design of the interfaces, which are easily understandable and do not require much cognitive effort from the side of the healthcare professionals. The same healthcare providers can always be involved in designing new interfaces so that the new proxies fit into the existing environment.

Finally, it is safe to state that HCI in healthcare holds great potential for growth and can become an essential tool in delivering patient care. However, these advantages cannot be achieved without addressing the ethical, privacy, and pragmatic concerns that come with adopting new technologies. This means embracing interdisciplinarity and keeping the patients at the center to create interfaces and designs that not only take advantage of the best the technology industry has to offer but also deliver the best in terms of the quality and availability of healthcare. In the future, the nursing profession must carefully consider critical areas as technology continues to evolve, balancing innovation with effective implementation to ensure the best outcomes for the patients.

7. Conclusions

This review delineates the fundamental contribution of HCI to changing the topography of healthcare. Based on user-centered design practices, HCI serves as an instrument providing technological interfaces and a revolution in healthcare, directing toward more productive patient-oriented and collaborative networks. This incorporation of wearable devices, AI, VR, and IoT is progressing not just in technology but also in powerful hardware for driving human-centric care, a powerful call to action for interactive interfaces to be adapted in medical institutes. The evidence presented highlights the viability of HCI to streamline treatment processes, increase patient involvement, and improve overall healthcare performance. Adapting to this change requires collective efforts from institutions and practitioners, allowing a convergence of technology with compassionate healthcare delivery. Ahead of us, the future of HCI in healthcare is bright if we advance guided by a commitment to ethical design, user-centric approaches, and ongoing interdisciplinary collaborations. The trip ahead invites us to utilize HCI as a facilitator of an environment in the healthcare sector that fully incorporates technology while being people centric.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflicts of interest.

Author contributions

Meher Langote, Saniya Saratkar, and Praveen Kumar wrote the manuscript and drew figures and tables. Prateek Verma, Chetan Puri, Swapnil Gundewar and Palash Gourshettiwar provided the conceptual idea and revised the manuscript. All authors have read and approved the final manuscript.

References

1. Sawesi S, Rashrash M, Phalakornkule K, et al. (2016) The impact of information technology on patient engagement and health behavior change: A systematic review of the literature. *JMIR Med Inf* 4: e4514. https://doi.org/10.2196/medinform.4514

2. Søgaard Neilsen A, Wilson RL (2019) Combining e-mental health intervention development with human computer interaction (HCI) design to enhance technology-facilitated recovery for people with depression and/or anxiety conditions: An integrative literature review. *Int J Ment Health Nu* 28: 22–39. https://doi.org/10.1111/inm.12527

3. Mishra R, Satpathy R, Pati B (2023) Human computer interaction applications in healthcare: An integrative review. *EAI Endorsed T Pervas Health Technol* 9. https://doi.org/10.4108/eetpht.9.4186

4. Melles M, Albayrak A, Goossens R (2021) Innovating health care: Key characteristics of human-centered design. *Int J Qual Health C* 33: 37–44. https://doi.org/10.1093/intqhc/mzaa127

5. He X, Hong Y, Zheng X, et al. (2023) What are the users' needs? Design of a user-centered explainable artificial intelligence diagnostic system. *Int J Hum–Comput Int* 39: 1519–1542. https://doi.org/10.1080/10447318.2022.2095093

6. Cornelio P, Haggard P, Hornbaek K, et al. (2022) The sense of agency in emerging technologies for human–computer integration: A review. *Front Neurosci* 16: 949138. https://doi.org/10.3389/fnins.2022.949138

7. Sadeghi Milani A, Cecil-Xavier A, Gupta A, et al. (2024) A systematic review of human–computer interaction (HCI) research in medical and other engineering fields. *Int J Hum–Comput Int* 40: 515–536. https://doi.org/10.1080/10447318.2022.2116530

8. Reimer YJ, Douglas SA (2003) Teaching HCI design with the studio approach. *Comput Sci Educ* 13: 191–205. https://doi.org/10.1076/csed.13.3.191.14945

9. Siek KA (2018) Expanding human computer interaction methods to understand user needs in the design process of personal health systems. *Yearb Med Inf* 27: 74–78. https://doi.org/10.1055/s-0038-1667073

10. Jimison HB, Pavel M, Parker A, et al. (2023) Correction to: The role of human computer interaction in consumer health applications: Current state, challenges and the future, In: Patel VL, Kannampallil TG, Kaufman DR, *Cognitive Informatics for Biomedicine. Health Informatics*, Berlin: Springer, 259–278. https://doi.org/10.1007/978-3-319-17272-9_15

11. Saliba V, Legido-Quigley H, Hallik R, et al. (2012) Telemedicine across borders: A systematic review of factors that hinder or support implementation. *Int J Med Inform* 81: 793–809. https://doi.org/10.1016/j.ijmedinf.2012.08.003

12. Almathami HKY, Win KT, Vlahu-Gjorgievska E (2020) Barriers and facilitators that influence telemedicine-based, real-time, online consultation at patients' homes: Systematic literature review. *J Med Internet Res* 22: e16407. https://doi.org/10.2196/16407

13. Wang D, Yang Q, Abdul A, et al. (2019) Designing theory-driven user-centric explainable AI. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* 1–15. https://doi.org/10.1145/3290605.3300831

14. Dearden A, Finlay J (2006) Pattern languages in HCI: A critical review. *Hum–Comput Interact* 21: 49–102. https://doi.org/10.1207/s15327051hci2101_3

15. Mackay WE, Fayard AL (1997) HCI, natural science and design: A framework for triangulation across disciplines. *Proceedings of the 2nd Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques* 223–234. https://doi.org/10.1145/263552.263612

16. Gulliksen J, Göransson B, Boivie I, et al. (2003) Key principles for user-centred systems design. *Behav Inform Technol* 22: 397–409. https://doi.org/10.1080/01449290310001624329

17. Pacini Naumovich ER, Mateos Diaz CM, Garcia Garino CG (2015) Balancing throughput and response time in online scientific Clouds via Ant Colony Optimization (SP2013/2013/00006). *Adv Eng Softw* 84: 31–47. https://doi.org/10.1016/j.advengsoft.2015.01.005

18. Frangoudes F, Hadjiaros M, Schiza EC, et al. (2021) An overview of the use of chatbots in medical and healthcare education. *International Conference on Human-Computer Interaction* 170–184. https://doi.org/10.1007/978-3-030-77943-6_11

19. Pavlovic VI, Sharma R, Huang TS (1997) Visual interpretation of hand gestures for human-computer interaction: A review. *IEEE T Pattern Anal* 19: 677–695. https://doi.org/10.1109/34.598226

20. Spruit M, Lytras M (2018) Applied data science in patient-centric healthcare: Adaptive analytic systems for empowering physicians and patients. *Telemat Inform* 35: 643–653. https://doi.org/10.1016/j.tele.2018.04.002

21. Hegner SM, Beldad AD, Brunswick GJ (2019) In automatic we trust: Investigating the impact of trust, control, personality characteristics, and extrinsic and intrinsic motivations on the acceptance of autonomous vehicles. *Int J Hum–Comput Int* 35: 1769–1780. https://doi.org/10.1080/10447318.2019.1572353

22. Ekstrand MD, Das A, Burke R, et al. (2022) Fairness in information access systems. *Found Trends Inf Ret* 16: 1–177. https://doi.org/10.1561/1500000079

23. Finstad K (2010) The usability metric for user experience. *Interact Comput* 22: 323–327. https://doi.org/10.1016/j.intcom.2010.04.004

24. Ke JXC, George RB, Wozney L, et al. (2021) Application mobile périopératoire destinée aux mères avec un accouchement par césarienne: Une étude de cohorte prospective sur l'intérêt des patientes. *Can J Anesth* 68: 505–513. https://doi.org/10.1007/s12630-020-01907-x

25. Robbins DA, Curro FA, Fox CH (2013) Defining patient-centricity: Opportunities, challenges, and implications for clinical care and research. *Ther Innov Regul Sci* 47: 349–355. https://doi.org/10.1177/2168479013484159

26. Visell Y (2009) Tactile sensory substitution: Models for enaction in HCI. *Int Comput* 21: 38–53. https://doi.org/10.1016/j.intcom.2008.08.004

27. Bukht TFN, Rahman H, Shaheen M, et al. (2024) A review of video-based human activity recognition: Theory, methods and applications. *Multimed Tools Appl* 1–47. https://doi.org/10.1007/s11042-024-19711-w

28. Holden RJ, Abebe E, Hill JR, et al. (2022) Human factors engineering and human-computer interaction: Supporting user performance and experience. *Clinic Inf Stu Guide* 119–132. https://doi.org/10.1007/978-3-030-93765-2_9

29. Dino MJS, Davidson PM, Dion KW, et al. (2022) Nursing and human-computer interaction in healthcare robots for older people: An integrative review. *Int J Nurs Stu Adv* 4: 100072. https://doi.org/10.1016/j.ijnsa.2022.100072

30. Luo Y, Li M, Tang J, et al. (2021) Design of a virtual reality interactive training system for public health emergency preparedness for major emerging infectious diseases: Theory and framework. *JMIR Serious Games* 9: e29956. https://doi.org/10.2196/29956

31. Ahmed A, Xi R, Hou M, et al. (2023) Harnessing big data analytics for healthcare: A comprehensive review of frameworks, implications, applications, and impacts. *IEEE Access*. https://doi.org/10.1109/ACCESS.2023.3323574

32. Pierce J, Sengers P, Hirsch T, et al. (2015) Expanding and refining design and criticality in HCI. *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* 2083–2092. https://doi.org/10.1145/2702123.2702438

33. Bachmann D, Weichert F, Rinkenauer G (2018) Review of three-dimensional human-computer interaction with focus on the leap motion controller. *Sensors* 18: 2194. https://doi.org/10.3390/s18072194

34. Šumak B, Brdnik S, Pušnik M (2021) Sensors and artificial intelligence methods and algorithms for human–computer intelligent interaction: A systematic mapping study. *Sensors* 22: 20. https://doi.org/10.3390/s22010020

35. Shah SA, Fioranelli F (2019) RF sensing technologies for assisted daily living in healthcare: A comprehensive review. *IEEE Aero El Sys Mag* 34: 26–44. https://doi.org/10.1109/MAES.2019.2933971

36. Omaghomi TT, Elufioye OA, Akomolafe O, et al. (2024) Health apps and patient engagement: A review of effectiveness and user experience. *World J Adv Res Rev* 21: 432–440. https://doi.org/10.30574/wjarr.2024.21.2.0476

37. Oulasvirta A, Hornbæk K (2016) HCI research as problem-solving. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* 4956–4967. https://doi.org/10.1145/2858036.2858283

38. Hekler EB, Klasnja P, Froehlich JE, et al. (2013) Mind the theoretical gap: Interpreting, using, and developing behavioral theory in HCI research. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* 3307–3316. https://doi.org/10.1145/2470654.2466452

39. Su T, Ding Z, Cui L, et al. (2024) System development and evaluation of human–computer interaction approach for assessing functional impairment for people with mild cognitive impairment: A pilot study. *Int J Hum–Comput Int* 40: 1906–1920. https://doi.org/10.1080/10447318.2023.2228529

40. Sin J, Munteanu C (2020) An empirically grounded sociotechnical perspective on designing virtual agents for older adults. *Hum–Comput Int* 35: 481–510. https://doi.org/10.1080/07370024.2020.1731690

41. Mentler T, Berndt H, Herczeg M (2016) Optical head-mounted displays for medical professionals: Cognition-supporting human-computer interaction design. *Proceedings of the European Conference on Cognitive Ergonomics* 1–8. https://doi.org/10.1145/2970930.2970957

42. Girju R, Girju M (2022) Design considerations for an NLP-driven empathy and emotion interface for clinician training via telemedicine. *Proceedings of the Second Workshop on Bridging Human-Computer Interaction and Natural Language Processing* 21–27. https://doi.org/10.18653/v1/2022.hcinlp-1.3

43. Dix A (2017) Human–computer interaction, foundations and new paradigms. *J Visual Lang Comput* 42: 122–134. https://doi.org/10.1016/j.jvlc.2016.04.001

44. Prasad S, Smith A, Joshi A, et al. (2005) Report on the first all-India human-computer interaction conference. *Interact* 12: 67–69. https://doi.org/10.1145/1082369.1082417

45. Balcombe L, De Leo D (2022) Human-computer interaction in digital mental health. *Informatics* 9: 14. https://doi.org/10.3390/informatics9010014

46. Chen S, Epps J, Ruiz N, et al. (2011) Eye activity as a measure of human mental effort in HCI. *Proceedings of the 16th international conference on Intelligent user interfaces* 315–318. https://doi.org/10.1145/1943403.1943454

47. Webster J, Trevino LK, Ryan L (1993) The dimensionality and correlates of flow in human-computer interactions. *Comput Hum Behav* 9: 411–426. https://doi.org/10.1016/0747-5632(93)90032-N

48. Ghani JA, Deshpande SP (1994) Task characteristics and the experience of optimal flow in human—computer interaction. *J Psychol* 128: 381–391. https://doi.org/10.1080/00223980.1994.9712742

49. Middleton B, Bloomrosen M, Dente MA, et al. (2013) Enhancing patient safety and quality of care by improving the usability of electronic health record systems: Recommendations from AMIA. *J Am Med Inform Asso* 20: e2–e8. https://doi.org/10.1136/amiajnl-2012-001458

50. Zheng K, Ratwani RM, Adler-Milstein J (2020) Studying workflow and workarounds in electronic health record–supported work to improve health system performance. *Ann Intern Med* 172: S116–S122. https://doi.org/10.7326/M19-0871

51. Zhang J, Johnson TR, Patel VL, et al. (2003) Using usability heuristics to evaluate patient safety of medical devices. *J Biomed Inform* 36: 23–30. https://doi.org/10.1016/S1532-0464(03)00060-1

52. Bolgova KV, Kovalchuk SV, Balakhontceva MA, et al. (2020) Human computer interaction during clinical decision support with electronic health records improvement. *Int J E-Health Med C* 11: 93–106. https://doi.org/10.4018/978-1-7998-9023-2.ch062

53. Mansur SH, Moran K (2023) Toward automated tools to support ethical GUI design. *2023 IEEE/ACM 45th International Conference on Software Engineering: Companion Proceedings* 294–298. https://doi.org/10.1109/ICSE-Companion58688.2023.00079

54. Aronson AR, Lang FM (2010) An overview of MetaMap: Historical perspective and recent advances. *J Am Med Inform Asso* 17: 229–236. https://doi.org/10.1136/jamia.2009.002733

55. Rossi S, Hallett M, Rossini PM, et al. (2009) Safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research. *Clin Neurophysiol* 120: 2008–2039. https://doi.org/10.1016/j.clinph.2009.08.016

56. Doebelin N, Kleeberg R (2015) Profex: A graphical user interface for the rietveld refinement program BGMN. *J Appl Crystallogr* 48: 1573–1580. https://doi.org/10.1107/S1600576715014685

57. Kokalj A (2003) Computer graphics and graphical user interfaces as tools in simulations of matter at the atomic scale. *Comput Mater Sci* 28: 155–168. https://doi.org/10.1016/S0927-0256(03)00104-6

58. Xierali IM, Hsiao CJ, Puffer JC, et al. (2013) The rise of electronic health record adoption among family physicians. *Annal Fam Med* 11: 14–19. https://doi.org/10.1370/afm.1461

59. Park A, Wilson M, Robson K, et al. (2023) Interoperability: Our exciting and terrifying Web3 future. *Bus Horizons* 66: 529–541. https://doi.org/10.1016/j.bushor.2022.10.005

60. Keshta I, Odeh A (2021) Security and privacy of electronic health records: Concerns and challenges. *Egypt Inform J* 22: 177–183. https://doi.org/10.1016/j.eij.2020.07.003

61. Nazar M, Alam MM, Yafi E, et al. (2021) A systematic review of human–computer interaction and explainable artificial intelligence in healthcare with artificial intelligence techniques. *IEEE Access* 9: 153316–153348. https://doi.org/10.1109/ACCESS.2021.3127881

62. Ledo D, Houben S, Vermeulen J, et al. (2018) Evaluation strategies for HCI toolkit research. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* 1–17. https://doi.org/10.1145/3173574.3173610

63. Barricelli BR, Fogli D (2024) Digital twins in human-computer interaction: A systematic review. *Int J Hum–Comput Int* 40: 79–97. https://doi.org/10.1080/10447318.2022.2118189

64. Blandford A (2019) HCI for health and wellbeing: Challenges and opportunities. *Int J Hum-Comput St* 131: 41–51. https://doi.org/10.1016/j.ijhcs.2019.06.007

65. Hornbæk K (2006) Current practice in measuring usability: Challenges to usability studies and research. *Int J Hum-Comput St* 64: 79–102. https://doi.org/10.1016/j.ijhcs.2005.06.002

66. Lewis JR (1995) IBM computer usability satisfaction questionnaires: Psychometric evaluation and instructions for use. *Int J Hum–Comput Int* 7: 57–78. https://doi.org/10.1080/10447319509526110

67. Jaspers MW (2009) A comparison of usability methods for testing interactive health technologies: Methodological aspects and empirical evidence. *Int J Med Inform* 78: 340–353. https://doi.org/10.1016/j.ijmedinf.2008.10.002

68. Sadeghi Milani A, Cecil-Xavier A, Gupta A, et al. (2024) A systematic review of human–computer interaction (HCI) research in medical and other engineering fields. *Int J Hum–Comput Int* 40: 515–536. https://doi.org/10.1080/10447318.2022.2116530

69. Chandra S, Sharma G, Malhotra S, et al. (2015) Eye tracking based human computer interaction: Applications and their uses. *2015 International Conference on Man and Machine Interfacing* 1–5. https://doi.org/10.1109/MAMI.2015.7456615

70. Newell AF, Gregor P (1997) Human computer interfaces for people with disabilities, *Handbook of Human-Computer Interaction*, Holland: North-Holland. 813–824. https://doi.org/10.1016/B978-044481862-1.50101-1

71. Aggarwal JK, Ryoo MS (2011) Human activity analysis: A review. *Acm Comput Surv* 43: 1–43. https://doi.org/10.1145/1922649.1922653

72. Maes P (1995) Agents that reduce work and information overload, *Readings in Human–Computer Interaction*, Manhattan: Morgan Kaufmann. 811–821. https://doi.org/10.1016/B978-0-08-051574-8.50084-4

73. Judd T, Ehinger K, Durand F, et al. (2009) Learning to predict where humans look. *2009 IEEE 12th International Conference on Computer Vision* 2106–2113. https://doi.org/10.1109/ICCV.2009.5459462

74. Dalsgaard P, Dindler C (2014) Between theory and practice: Bridging concepts in HCI research. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* 1635–1644. https://doi.org/10.1145/2556288.2557342

75. Stephanidis C, Salvendy G, Antona M, et al. (2019) Seven HCI grand challenges. *Int J Hum–Comput Int* 35: 1229–1269. https://doi.org/10.1080/10447318.2019.1619259

76. Fukizi KY (2023) Collaborative decision-making assistant for healthcare professionals: A human-centered AI prototype powered by azure open AI. *Proceedings of the 6th ACM SIGCAS/SIGCHI Conference on Computing and Sustainable Societies* 118–119. https://doi.org/10.1145/3588001.3609370

77. Ala A, Simic V, Pamucar D, et al. (2024) Enhancing patient information performance in internet of things-based smart healthcare system: Hybrid artificial intelligence and optimization approaches. *Eng Appl Artif Intel* 131: 107889. https://doi.org/10.1016/j.engappai.2024.107889

78. Han E, DeVeaux C, Miller MR, et al. (2024) Alone together, together alone: The effects of social context on nonverbal behavior in virtual reality. *Presence-Virtual Aug* 33: 425–451. https://doi.org/10.1162/pres_a_00432

79. Greenberg S, Boring S, Vermeulen J, et al. (2014) Dark patterns in proxemic interactions: A critical perspective. *Proceedings of the 2014 conference on Designing interactive systems* 523–532. https://doi.org/10.1145/2598510.2598541

80. Epstein DA, O'Kane AA, Miller AD (2023) Symposium: Workgroup on interactive systems in healthcare (WISH). *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems* 1–4. https://doi.org/10.1145/3544549.3573804

81. Yarmand M, Chen C, Cheng K, et al. (2024) "I'd be watching him contour till 10 o'clock at night": Understanding tensions between teaching methods and learning needs in healthcare apprenticeship. *Proceedings of the CHI Conference on Human Factors in Computing Systems* 1–19. https://doi.org/10.1145/3613904.3642453