ChatGPT

Recent Developments in Human Factors Research (2019–2024)

Introduction

Human factors (HF) research examines how people interact with technology, systems, and environments, aiming to improve safety, performance, and well-being. In the past five years, rapid technological change and global events have significantly influenced human factors across domains. The rise of artificial intelligence (AI) and automation, the COVID-19 pandemic's shift to remote work, and a growing emphasis on **human-centered design** have all driven new research themes. Broadly, recent HF research highlights the need to integrate human considerations early in system design, ensuring that emerging technologies (from autonomous vehicles to AI decision support) are **usable, trustworthy, and aligned with human capabilities** [1] [2]. There is also a noticeable shift from treating humans as sources of error to viewing humans as **sources of resilience** in complex systems [3] [4]. This report provides a comprehensive overview of recent human factors developments by domain, covering emerging themes, key innovations, methodological shifts, trends in human error and cognitive load, the impact of AI/automation, integration with data science and systems engineering, and relevant regulatory or standards changes.

Aviation and Aerospace

In aviation and aerospace, human factors research has focused on safely integrating **advanced automation and new vehicle types** into operations. Emerging aviation markets – such as unmanned aircraft systems (UAS) and urban air mobility (UAM) – present new HF challenges, including remote or single-pilot supervision of highly automated vehicles [5] [6]. Research emphasizes designing automation that keeps pilots and air traffic controllers in the loop without overloading them. For example, modern airliners now involve pilots directly controlling the aircraft for only a few minutes per flight, spending most time **monitoring complex automation**, which can erode skills and lead to issues like "mode confusion" or automation surprises [7] [8]. To address this, studies have stressed improved **automation transparency** and training for rare intervention scenarios. NASA and others underscore the need for **human-machine teaming (HMT)** approaches that foster appropriate roles for AI and humans – but also warn of *trust miscalibration* (either over-trust or under-trust in automation) if systems behave unexpectedly [9] [10]. Ensuring calibrated trust may require better explainability in cockpit decision aids and new training paradigms to help pilots manage AI-based systems [11] [9].

Another active area is the **use of data science and physiological sensing** to enhance aviation safety. Recent work leverages machine learning on pilot psychophysiological data (e.g. heart rate, EEG) to detect pilot fatigue, workload, and emotional states in real time [12] [13]. A 2024 systematic review noted a surge in studies using wearables and AI algorithms to predict or prevent human performance issues in flight, with most focusing on workload and fatigue detection [14] [15]. Although deep learning techniques are still emerging in this area, such data-driven approaches are seen as promising for **adaptive automation** that could, for instance, alert a drowsy pilot or adjust interface complexity based on workload [15] [16]. Complementing this, the concept of **resilience engineering** has gained traction in aviation training –

encouraging crews to adapt to unexpected situations. Studies on private and commercial pilots highlight training for **resilience and adaptability** to handle abnormal situations (e.g. system failures or novel scenarios) as an important trend [17] [18].

The integration of AI is also influencing **air traffic management and safety analytics**. Aviation safety management systems are evolving "in-time" safety monitoring that uses big data and AI to predict risks in the National Airspace System. Human factors researchers are involved in designing these tools so that safety analysts can trust and effectively use AI predictions [11] [19]. There is a push for **human-centric visual analytics** – e.g. interactive safety dashboards – that allow human decision-makers to sift through AI outputs and massive datasets intuitively [11] [19]. Regulatory bodies have also responded: in the wake of automation-related accidents (such as the 737 MAX incidents), **authorities now mandate more rigorous human factors evaluations** in aircraft certification and pilot training updates. Overall, aviation human factors research (2019–2024) centers on balancing advanced technology with human abilities through improved interface design, training for automation surprises, monitoring of human states, and building resilient human-machine teams to maintain safety in increasingly autonomous flight operations.

Healthcare and Medical Systems

Human factors in healthcare has rapidly expanded in scope, reflecting the digital transformation of medicine. A **major trend is the infusion of AI and data-driven tools** into healthcare and the corresponding need for human-centered design of these technologies. Recent reviews (2022–2023) indicate a sharp increase in studies on **AI in healthcare**, from diagnostic decision support to workflow optimization, with an emphasis on usability, clinician trust, and ethical concerns [20] [21]. For example, clinical AI systems now assist in reading radiology images or predicting patient deterioration, but human factors research has shown that *user trust and oversight* are critical – users must understand the AI's suggestions and limitations [21] [22]. This has spurred work on **explainable AI in healthcare** and on training clinicians to effectively collaborate with AI (treating it as a "team member" rather than an oracle). Studies have examined barriers and facilitators to AI adoption, finding that clear benefits, transparency, and alignment with clinical workflows improve trust, whereas opaque "black-box" models or workflow disruptions hinder acceptance [21] [22].

Concurrently, there's been enormous growth in **patient-facing health technology** and related human factors. The pandemic catalyzed adoption of telemedicine, remote patient monitoring, and mobile health (mHealth) apps. HF researchers have evaluated telehealth interfaces and *hospital-at-home* setups, identifying issues such as **video consultation fatigue, data privacy concerns, and the need for intuitive monitoring devices for laypersons** [23] [24]. Studies on remote patient monitoring highlight challenges in ensuring patients actually use devices correctly and are not overwhelmed – trust, privacy, and data confidentiality emerged as key factors for patient acceptance of wearables and home sensors [24] [25]. Another burgeoning area is **healthcare IoT usability**: as hospitals implement interconnected devices (smart pumps, sensor networks), human factors efforts focus on interface consistency, alarm management, and preventing data overload or breaches through better design [26] [27].

Healthcare human factors has also embraced **systems approaches and multi-level analysis**. Frameworks like the SEIPS (Systems Engineering Initiative for Patient Safety) have been widely applied to understand not just individual usability, but how technology fits into complex clinical workflows and organizational culture [28] [29]. For instance, *patient safety culture* and organizational factors (staff communication, workload, policies) are now examined alongside interface design. Over the last five years, more studies target *macro-*

level issues such as **team coordination in the operating room, handoff communication, and institutional resilience**, reflecting an understanding that safe healthcare requires aligning technology with social and organizational processes [1] [28]. Methodologically, there's been a shift toward **real-world and remote evaluations**: in addition to lab simulations, researchers use in situ observations, *naturalistic usability studies*, and even remote user testing (a trend accelerated by COVID-19) to capture how systems perform in practice [30] [31].

Key innovations in this period include **augmented and virtual reality for medical training and care**. VR simulations are used for surgical training and practicing rare emergency scenarios, benefiting from high fidelity while maintaining safety. AR is being explored for guiding surgeons (e.g. overlaying imaging on patients during procedures) and for patient education, showing promising results in improving understanding [32] [33]. **Robotics in healthcare** have also advanced – from surgical robots to social robots for elder care – and HF research examines user experience with these robots, emphasizing qualities like *empathy and communication* in robot design to improve patient comfort [34] [35]. Regulatory-wise, there is increasing pressure for **usability in medical device approvals**. Standards such as IEC 62366 (medical device usability engineering) were updated, and regulators (e.g. U.S. FDA) now routinely require human factors evidence to ensure that new devices (like insulin pumps or infusion pumps) can be used safely and effectively. In summary, healthcare human factors (2019–2024) has broadened from a focus on reducing **human error** to enhancing overall *system usability, safety, and user well-being*, in an era of AI-assisted, connected, and patient-centered care [36] [37].

Automotive and Autonomous Vehicles

The automotive sector has seen transformative developments with automated driving technologies, and human factors research in the last five years has concentrated on the **human–automation interaction** in vehicles. As cars progress from advanced driver assistance systems (ADAS) to higher levels of autonomy, a critical theme is the management of **driver attention, trust, and control transitions**. Studies have found that partially automated driving (SAE Level 2–3 systems like highway lane centering or traffic jam assist) can lead to driver over-reliance or conversely, distrust, depending on system design and user education. A key trend is designing **Human-Machine Interfaces (HMIs) for shared control**, where the vehicle can handle routine tasks but the human must re-engage when needed. Research has highlighted the need for effective **takeover alerts and handoff procedures** – for instance, using multi-modal alerts (audio, visual, haptic) and giving drivers sufficient lead time to regain situational awareness during an autonomous-to-manual transition [38] [39]. HMI design for these scenarios is evolving: recent papers propose adaptive interfaces that monitor driver state (via cameras tracking gaze or head position) and tailor alerts accordingly (e.g. more urgent or intrusive alerts if the driver appears distracted). The **driver monitoring systems (DMS)** themselves have become mainstream – Europe's *General Safety Regulation (GSR)* now mandates driver drowsiness and attention warning systems in all new vehicles by 2024 [40] [41]. This regulatory push is grounded in HF findings that such monitoring, if used to issue timely warnings, can mitigate accidents caused by fatigue or inattention.

Trust in automation is another major research area. **Trust calibration** is crucial: drivers should trust autonomous features enough to use them, but not so blindly that they become complacent. Studies show that *system transparency* and feedback can increase appropriate trust – for example, interfaces that display the AI's understanding (highlighting detected vehicles or road markings) help users know when the system is perceiving correctly [42] [43]. Conversely, unpredictable system behavior (e.g. automatic braking "false alarms") can quickly undermine trust. Human factors experiments have evaluated various approaches to maintain calibrated trust, such as **driver training simulators** for automated systems, and **in-vehicle explainability** (the car explaining why it's handing back control or why it's slowing down) [44] [45]. External HMI is also emerging: as fully autonomous vehicles (without human drivers) are tested, researchers developed **external communication displays** (like signals to pedestrians) to convey intent, since eye contact with a driver is no longer possible. Early studies (2021–2024) on these external HMIs find they can improve pedestrian confidence and crossing decisions, though standardization will be needed across industry.

Methodologically, automotive HF research has increasingly used **high-fidelity driving simulators and test tracks** to study human behavior with automated systems safely. There's also a trend toward *inclusive design* in vehicle HMIs – recognizing that interfaces must accommodate a wide range of drivers (older adults, persons with disabilities, etc.). For instance, an inclusive HMI study in 2022 identified fundamental interaction changes needed for shared autonomous shuttles (where riders are passengers, not drivers) and highlighted the importance of accessibility (e.g. voice interfaces for visually impaired users, simple language) in these vehicles [46] [47]. In line with this, human factors engineers are rethinking **vehicle interior design** for a future where occupants might engage in non-driving tasks: seat layouts, infotainment systems, and even **motion sickness mitigation** (via smoother automation or adjustable lighting) are being researched to improve comfort and usability when people are not actively driving.

Regulatory and standards developments reflect human factors insights. Europe's new safety rules (2022–2024) require many **advanced driver assistance features** (intelligent speed assistance, lane-keeping aids, collision warning) on all new cars [40]. This effectively mainstreams technologies that HF researchers have worked on for years, such as the best ways to alert drivers to speeding or lane departure. The UN/ECE also introduced regulations for *Level 3 automated systems* (e.g. Automated Lane Keeping Systems) that include human factors requirements like driver availability monitoring and transition demand protocols. In the US, NHTSA has issued interface guidelines for ADAS to minimize distraction and ensure clarity. Overall, recent human factors work in automotive focuses on ensuring **human drivers remain engaged, informed, and in ultimate control** even as vehicles grow more autonomous – and on designing the car's interfaces and behavior to support a safe and smooth partnership between human and AI driver [6] [48].

Human–Computer Interaction and UX/UI

Human–Computer Interaction (HCI) and user experience (UX) research from 2019 to 2024 has been marked by several broad trends driven by emerging technologies and societal needs. One overarching theme is the integration of **AI into user interfaces** – ranging from voice assistants and chatbots to personalized recommendations – and the need to maintain usability, transparency, and user trust. Interfaces are increasingly powered by AI (e.g. smart home systems or AI-driven content feeds), prompting HCI research into **explainable and controllable UX**. For instance, designers now consider how to let users intervene in or understand algorithmic decisions (such as why a certain recommendation is shown), aiming to make AI more *human-centered* rather than opaque. This aligns with the HCI community's push for a "human-technology symbiosis," where technology augments human abilities in a cooperative manner [49] [50]. A 2025 "grand challenges" update in HCI emphasized that progress in **human–AI symbiosis** requires interfaces that adapt to users, convey AI reasoning, and allow meaningful human oversight [2] [51].

Another significant trend is the expansion of **natural and immersive interaction modalities**. Advancements in *voice and gesture recognition* have made conversational user interfaces and touchless interactions much more common in the last five years [2]. Voice user interfaces (VUIs) – think smart speakers or voice control in cars – have been refined for better accuracy and user acceptance, with research addressing issues like dialogue design, error handling, and privacy (since always-listening devices raise concerns). Gesture and body-motion interfaces, often combined with **augmented/virtual reality (AR/VR)**, are also flourishing. AR/VR technologies have matured and become important in domains like education, gaming, and training, so HCI research has tackled usability challenges specific to immersive environments (for example, minimizing VR-induced motion sickness, designing intuitive 3D navigation controls, and ensuring **hand-tracking or haptic feedback** devices align with user expectations) [52] [53]. The proliferation of AR/VR has also led to novel UI metaphors and the need to establish usability heuristics for these environments, which differ from traditional desktop or mobile interfaces.

Accessibility and inclusive design have gained even greater focus in UX research and practice. There's a growing recognition that products must be usable by people with diverse abilities, ages, and backgrounds. In recent years, we've seen updates to accessibility standards (e.g. W3C's WCAG 2.2 guidelines in 2023) and an emphasis on *universal design*. HCI research has contributed new tools for designers, such as automated accessibility checkers, and explored interfaces for people with disabilities – for instance, improved eye-tracking interfaces for users with motor impairments, or haptic and audio feedback schemes for visually impaired smartphone users. Inclusivity is also examined in emerging tech: ensuring that voice assistants recognize different accents and dialects, that VR can be used by those with limited mobility, and that **AI systems do not propagate bias** that could harm certain user groups (an ethical UX concern). In sum, **ethics, privacy, and user well-being** are now central considerations in HCI. From dark pattern prevention (avoiding deceptive UX techniques) to data privacy controls (designing clearer consent dialogs and privacy dashboards), UX professionals and researchers are working to align interfaces with users' rights and mental health. For example, studies on **"Zoom fatigue"** during the pandemic shed light on how continuous video meetings cause anxiety and exhaustion due to excessive eye contact and cognitive load [54] [55]. In response, interface changes (like hide-self-view options, or embedded break reminders) and best practices (limiting meeting length) were proposed to mitigate videoconferencing fatigue [56].

Methodologically, HCI research has embraced more **data-driven and interdisciplinary approaches**. Usability testing can now incorporate analytics from large user populations (e.g. A/B testing on live software, or analyzing interaction logs with machine learning to find pain points). There is also an increase in **remote user research methods** – unmoderated remote usability tests, experience sampling via apps, etc., which became crucial during COVID-19 and remain popular for reaching broader samples. HCI as a field continues to expand beyond traditional GUI concerns to encompass **smart environments (IoT)** and **ambient computing**. Researchers explore how humans interact with sensor-laden environments – for instance, smart homes that anticipate needs, or context-aware mobile apps – focusing on user control and trust in these *ubiquitous computing* scenarios. Additionally, the concept of **human-technology symbiosis** extends to blending physical and digital: tangible user interfaces and wearables are areas of innovation (e.g. devices like mixed-reality smart glasses, or interactive wearables that let users manipulate digital info through physical gestures).

In summary, HCI/UX in the past five years prioritizes creating experiences that are **intelligent but intelligible** – leveraging AI and new input/output technologies while keeping the human at the center of design. Key innovations include multimodal and immersive interfaces, whereas key challenges involve ensuring **usability, accessibility, and ethical transparency** across these new frontiers [2] [57]. The field's grand challenges, such as blending digital systems seamlessly into daily life and safeguarding user agency, are being actively addressed through both technological advances and human-centered design principles.

Industrial and Occupational Ergonomics

In industrial and occupational contexts (manufacturing, logistics, construction, etc.), human factors and ergonomics research has evolved to address the **Industry 4.0/5.0 era**, where workplaces are increasingly augmented with automation, robotics, and data analytics. A prominent development is the introduction of **wearable ergonomic technologies**, especially *exoskeletons*. Exoskeletons (wearable assistive devices for lifting or overhead work) are being explored to reduce worker musculoskeletal strain [58] [59]. Over the last few years, multiple field studies and trials have evaluated exoskeleton effectiveness in factories, warehouses, and even healthcare (for patient lifting). These studies show that exoskeletons *can* reduce muscle load and physical effort during repetitive tasks [59] [60]. However, human factors findings also highlight adoption barriers: **discomfort, heat, and movement constraints** often limit real-world use [59] [61]. Workers report that current exoskeleton designs can be cumbersome over long shifts, and "one size fits all" issues mean fit and adjustability are critical. Thus, recent research advocates for more **inclusive, user-centered exoskeleton design** and long-term evaluations. A 2025 scoping review stressed the need for context-sensitive, participatory design to ensure exoskeletons are safe, acceptable, and truly effective in diverse workplaces [62] [63]. The review also mapped how factors like professional identity (e.g. workers' pride in manual skill), organizational support, and social norms influence exoskeleton adoption – pointing to the importance of change management and worker training alongside the technology itself [64] [65].

Another major area is **collaborative robotics (cobots)** on factory floors. Unlike traditional industrial robots (kept behind fences), cobots work side by side with humans, taking on repetitive tasks while humans handle complex decisions. HF research on cobots in 2019–2024 has concentrated on **safety and trust** in human–robot collaboration. Technologically, cobots come with safety features (force limiting, vision systems to stop when a person is too close), but studies find that *workers' trust and acceptance* are equally vital. Many organizations report slower-than-expected cobot adoption because employees are unsure about safety or job impacts [66] [67]. Human factors work has therefore been examining how to cultivate appropriate trust: clear **mental models of what the robot will do**, consistent robot behavior, and involvement of workers in cobot implementation decisions improve trust and reduce anxiety. There is also recognition that **cobots introduce new risks** – not just physical (accidental contact), but cognitive and psychosocial. For example, if a cobot's behavior is unpredictable or if workers aren't properly trained on its capabilities, it can cause confusion or excessive monitoring burden. One study noted an inherent trade-off between a cobot's safety and its efficiency – overly conservative safety behaviors can frustrate workers and slow production, whereas higher speed can raise perceived risk [68] [69]. To manage this, a system-wide approach is suggested: beyond technical safety standards (like ISO/TS 15066 for cobot safety), organizations should assess **readiness** for human–robot teams, including worker attitudes and process adaptations [68] [70]. Researchers have even proposed *safety readiness assessment tools* to evaluate a workplace's maturity in areas such as training, change management, and risk awareness before cobot deployment [71].

The concept of **Industry 5.0 – human-centric, sustainable, and resilient industry –** has emerged as a guiding vision. This paradigm explicitly positions the *worker at the center* of production, using technology to *empower* rather than replace humans [72] [73]. In practice, this means designing workplaces where AI and automation handle tedious or dangerous tasks while humans focus on creative, decision-making, and craft aspects. Human factors contributions here include defining the role of the **"Operator 4.0/5.0"** – a tech-augmented worker – and ensuring interfaces for advanced manufacturing systems are intuitive. For instance, operators might use AR glasses to get real-time data on machine performance or wear biometric sensors that inform adaptive work-rest schedules. Research shows such tools can boost productivity and safety, but only if designed with worker input and with *respect for human limitations*. Indeed, even as tasks become more automated, cognitive load can shift rather than disappear: a control-room operator might need to supervise dozens of automated processes (raising issues of vigilance and information overload). Thus, **cognitive ergonomics** of monitoring tasks is a hot topic, with solutions like alert prioritization, better visualization of system states, and AI assistance to highlight anomalies.

Human factors is also increasingly integrated into **systems engineering for industrial settings**. For example, digital twins (virtual models of factory systems) are being used to simulate not just equipment performance but also human workflow and ergonomics. This allows evaluation of workstation designs or shift schedules via modeling, incorporating human reliability data. There's a continuation of traditional ergonomics work (ensuring proper tool design, reducing repetitive strain injuries, optimizing human–machine interfaces on equipment), but now enhanced with **sensor data and analytics**. Wearable sensors can track posture and fatigue in real time; companies use these to inform ergonomic interventions (like reminding workers to stretch or flagging if someone's lifting with bad form). On the organizational side, recognition of **psychosocial factors** – stress, mental workload, autonomy – has grown. The pandemic's effect on frontline and remote workers spurred interest in occupational mental health, leading to standards like ISO 45003 (2021) for psychological health at work.

In summary, recent developments in industrial ergonomics focus on synergy between humans and new technologies: *augmenting human work with robotics and wearables while safeguarding safety, comfort, and agency*. Research and practice underscore designing **for adaptability and resilience**, meaning systems should flexibly allocate tasks between humans and machines depending on the situation (echoing the resilience engineering idea that humans provide essential adaptive capacity). Regulatory trends (e.g. updated machinery safety directives, collaborative robot guidelines) increasingly embed human factors requirements, ensuring that as factories become "smarter," they also become safer and more human-friendly places to work [73] [74].

Safety-Critical Systems and Resilience

Safety-critical domains – such as aviation safety management (beyond the cockpit), nuclear power, petrochemical plants, rail transportation, and healthcare's high-risk processes – have witnessed an important evolution in human factors approaches over the last five years. A clear trend is the shift toward **resilience engineering and Safety-II principles**. Traditional safety management (Safety-I) focused on eliminating human errors and treating humans as a liability; newer approaches recognize humans as a critical resource for system **flexibility and failure recovery** [3] [4]. This perspective views *safety not only as absence of error, but presence of resilience* – the ability to adapt and keep systems functioning under varying conditions [75]. Human factors researchers in high-risk industries are thus developing methods to assess and enhance system resilience. For example, in offshore operations, there are frameworks to evaluate how operators adjust to disturbances and how to train those adjustments [76]. In healthcare, as seen, commentary pieces have advocated integrating HF science with Safety-II to redesign workflows for *human capacity*, not just to prevent errors but to enable humans to succeed under pressure [77] [78].

Another development is the **increased use of data analytics and AI for safety monitoring**, paired with human oversight. Industries are deploying predictive algorithms to detect anomalies or signs of potential failure (e.g. sensors in a chemical plant predicting equipment faults). Human factors work here ensures that these complex "Safety 4.0" tools present information in *actionable, user-friendly ways* and that human operators remain engaged. For instance, control room interfaces are being redesigned to integrate AI-generated alerts, with attention to alarm design (avoiding alarm fatigue), visualization (so operators grasp trends quickly), and **decision support** that suggests corrective actions without undermining human authority. A NASA System-Wide Safety project paper in 2024 highlighted exactly this: as aviation moves to **in-time safety management** using big data, a human factor challenge is engendering *trust* in automated safety data systems while keeping humans in the loop for critical decisions [11] [19]. Solutions include **human-centered analytic tools** and training safety analysts in interpreting AI outputs.

Human reliability analysis (HRA) techniques have also advanced. Classic HRA methods (like THERP or HEART) are being augmented with modern approaches such as Bayesian Networks and data-driven models [79] [80]. A review in 2023 found that third-generation HRA methods leveraging Bayesian analysis are increasingly applied in aviation and other sectors to quantify human error probabilities, showing potential for better risk prediction [81] [82]. These methods allow incorporating not just static error probabilities but also context factors and dependency between human actions. The trend is toward more dynamic risk assessment where human performance variability is modeled (aligning with resilience notions). Furthermore, **functional resonance analysis method (FRAM)** and other systemic techniques are used to understand how everyday performance adjustments can both create and mitigate risk. This reflects a broader methodological shift: *from investigating single incidents to analyzing complex systems*, often using simulation, network modeling, and incident databases to identify patterns.

In terms of **interface design for safety-critical operations**, there's been progress in areas like **digital control rooms**. Many industries (nuclear, air traffic control, healthcare monitoring) are modernizing legacy interfaces with digital displays, touchscreen systems, and even AI assistants. HF research ensures that this modernization does not introduce new mode confusions or overload operators. Concepts like **ecological interface design** (EID) have continued to inform next-gen control displays, aiming to visualize the deep functional structure of systems so that operators can more easily detect anomalies and diagnose issues. Additionally, **procedure automation** (e.g. computerized procedure systems in nuclear plants) has been studied to maintain operator situation awareness and authority – ensuring that even if an automated procedure system guides actions, the human operator understands *why* and can intervene.

Regulatory and standards updates underscore human factors in safety-critical domains. For example, the nuclear industry has guidance on integrating HF into control system upgrades and license renewals; the FAA and EASA in aviation have introduced or revised human factors certification requirements for new automation (learning from incidents). In the rail sector, standards for **driver-machine interfaces** for newer train control systems include ergonomic requirements. And in the medical domain, as noted, regulators focus on *usability engineering* for devices – critical given that misuse can be life-threatening. Another important domain is **cybersecurity** for safety-critical systems, which has a human factors component: ensuring that security measures (like multi-factor authentication or alarm systems for cyber incidents) are designed in a user-centered way, since operator error or workarounds can compromise security.

Lastly, the pandemic taught lessons about **remote operations in safety-critical work** (e.g. remote control of processes, or distributed expert teams managing crises via teleconference). HF research is looking at the impact of remote/hybrid modalities on team communication, situation awareness, and decision speed in emergencies. Ensuring reliable technology and clear protocols for remote collaboration has become part of contingency planning for many safety-critical organizations.

In sum, human factors research in safety-critical systems is moving beyond preventing individual "human errors" to building organizations and tools that support human performance under variable conditions. Emphasis is placed on **training for adaptive skills**, *designing systems that are error-tolerant and transparent*, and promoting a safety culture that values human insights (encouraging reporting, learning, and flexibility). The confluence of resilience thinking, advanced analytics, and human-centered design is shaping a new generation of safety management approaches that acknowledge the complexity of socio-technical systems and the indispensable role of human adaptability in keeping them safe [83] [4].

Remote Work and Hybrid Collaboration

The period since 2020 saw an unprecedented experiment with remote work, and human factors/ergonomics research has quickly mobilized to study its effects. With millions of people shifting to **work from home (WFH)** during the COVID-19 pandemic, both benefits and challenges emerged, informing new HF considerations for remote and hybrid workplaces. On the positive side, remote work offers flexibility and eliminated commutes, and early studies noted improved work-life integration for some. However, numerous studies highlighted *negative impacts on physical and mental well-being* if remote work is not managed well [84] [85]. A systematic review of health impacts from 2020–2021 found consistent issues of **increased sedentary behavior, reduced physical activity, and prolonged screen time** among remote workers [84] [85]. Home offices often were impromptu – e.g. kitchen tables or couches – leading to ergonomic problems like poor posture and musculoskeletal strain. As a result, ergonomists have been creating guidelines for proper at-home workstation setup (chair support, screen height, etc.) and some companies provided employees with ergonomic furniture or accessories for home use.

Another widely discussed phenomenon is **"Zoom fatigue,"** reflecting the cognitive and emotional exhaustion from excessive video meetings. Research identified multiple causes: the **unnatural sustained eye contact**, the need to consciously interpret or perform non-verbal cues on camera, and seeing one's own image constantly all contribute to increased cognitive load and stress [54] [55]. Additionally, the blurring of boundaries – being "always on" via computer – led to feelings of being constantly monitored or onstage. To alleviate these issues, HF specialists and psychologists suggested best practices such as limiting consecutive video calls, encouraging *audio-only breaks*, or using features like hiding self-view and turning off video when not needed [56]. Some platforms responded with interface tweaks (for example, adding an option to disable self-view, or gentle prompts if meetings run long). These interventions align with a human factors goal: *redesigning virtual collaboration to better fit human cognitive rhythms* and reduce overload.

Communication and collaboration dynamics in remote teams have been another key topic. Without face-to-face interaction, teams risk reduced informal communication and trust. Studies using organizational surveys and telemetry data (email/meeting metadata) found that while employees could maintain productivity, many suffered from feelings of isolation, poorer team cohesion, and communication barriers – especially for complex or creative tasks that benefit from in-person interaction. In response, organizations experimented with virtual team-building activities, more structured check-ins, and collaboration tools (like digital whiteboards for brainstorming). HF research has examined the usability of these new tools and how they can replicate some benefits of co-located work. For instance, persistent chat channels (e.g. Slack or Teams) can recreate watercooler conversations to a degree, but can also *increase cognitive load* as workers juggle yet another communication stream. The concept of **"digital presenteeism"** has emerged: some remote workers feel pressure to show online availability (green status lights, quick email replies at all hours), which can lead to longer work hours and burnout. This led to discussions on **boundary management** – human factors guidance encourages establishing clear work/non-work boundaries when location no longer separates them. Some countries and companies implemented "right to disconnect" policies to address this.

From a technical HF standpoint, ensuring **reliable and user-friendly remote work technology** became essential. VPNs, remote desktops, and conferencing software had to scale up. User feedback drove many improvements to these systems over the last few years, focusing on simplicity and integration. For example, video conferencing UIs added features like noise cancellation (to reduce auditory distractions from home), virtual backgrounds (to protect privacy or reduce image fatigue), and better moderation controls (to manage large calls). Usability testing on these features ensured they meet user needs without adding complexity. Additionally, security was a concern (Zoombombing incidents, etc., showed the need for more user-friendly security settings – which were subsequently added).

Hybrid work (mix of remote and in-office) is now considered the new normal in many sectors, and presents its own HF challenges. Meetings with some people in-person and others remote can create an uneven playing field (remote participants may feel less included). To tackle this, companies are reconfiguring conference rooms with better audio/video to equally represent all participants, and training leaders to facilitate more deliberately (e.g. explicitly bringing remote folks into discussions). There is a trend of **experimenting with office designs** for hybrid work – creating collaboration spaces for those days people come in, while quiet focus work might be done at home. Human factors input is used to ensure these new spaces support diverse work modes and that *technology in meeting rooms* (cameras, smart whiteboards) is easy to use so meetings flow smoothly.

Another research angle is how remote work affects **performance and error**. Some studies in software engineering and other knowledge work indicated sustained or even improved output remotely, while others found drops in innovation or training efficiency for new employees. HF researchers emphasize the need for good **onboarding and knowledge sharing systems** in a hybrid world – e.g. using AR or interactive guides to train new workers remotely on physical equipment, or capturing tacit knowledge in digital forums since one can't as easily learn by "overhearing" in an office.

In summary, the human factors community's work on remote/hybrid collaboration (especially post-2020) centers on supporting **productivity, health, and social connection** outside traditional workplaces. Solutions include ergonomic interventions for home offices, better-designed collaboration software to reduce fatigue and friction, organizational policies to prevent burnout, and ensuring inclusivity in hybrid settings. This area remains active as both employees and employers refine what truly effective and sustainable remote/hybrid work looks like. Long-term, we can expect continued focus on *remote ergonomics*, *digital wellness*, and tools (possibly VR/AR meeting solutions) that try to combine the convenience of remote with the richness of face-to-face interaction – all guided by human factors evidence on what workers need for success and well-being.

Human–AI Teaming and Decision-Making

One of the most dynamic research frontiers in human factors is **human–AI teaming** – how humans and artificial agents can form effective teams for decision-making. As AI systems become more capable and autonomous, the interaction shifts from a traditional tool-user model to a *teammate model*, where AI might suggest options, execute tasks, or even take initiative. Recent literature defines human-AI teaming as scenarios where humans and AI agents work **interdependently** toward common goals, each contributing their strengths [86]. Achieving this requires both technical and human-centered advances. A recurring theme is the establishment of **appropriate trust, roles, and mutual understanding** between human and AI. Research shows that humans are willing to collaborate with AI, but trust must be earned and calibrated: if the AI performs well and explains its reasoning, trust increases; if it makes errors or acts opaquely, users may either over-rely (thinking it's infallible) or under-rely (ignore good suggestions), both of which are problematic [9] [87].

To foster *calibrated trust*, a lot of work has gone into **explainable AI (XAI)** and transparent algorithm design. For example, in intelligence analysis or medical diagnosis contexts, AI systems now often provide confidence levels or highlight the factors influencing their recommendation. Studies have demonstrated that such explanations (visualizations, feature importance, model reasoning in natural language, etc.) can help humans make better decisions with AI and adjust their trust level appropriately [44] [45]. One survey of human–AI teaming research found that explainability is frequently proposed as a means to improve collaboration, by enabling the human to understand *why* the AI is suggesting an action and thus be more willing to follow it (or catch its mistakes) [44] [45]. However, explanation must be carefully designed – too much detail can overwhelm, while too little may be unhelpful. Human factors researchers often test different explanation styles to see which best supports human comprehension and decision accuracy.

Teamwork dynamics like communication, shared mental models, and division of labor are being re-conceptualized for human-AI teams. There's interesting work on how to give AI a *"theory of mind"* about the human teammate – for instance, AI that can gauge when a user is confused or when it should defer to human judgment. Conversely, humans need a mental model of the AI's capabilities and limits. Recent experiments in domains such as military command simulations and emergency response have the AI proactively communicate its status ("I haven't encountered this scenario before, I may be less reliable") or ask questions, to build a more two-way partnership rather than one-sided command. The idea of AI as a **social entity** is gaining ground: some studies suggest using human team training concepts (like team trust building, cross-training) but applied to humans and AI. Indeed, papers have noted that with increased AI autonomy, machines should be considered *teammates and even social actors*, and thus human teamwork factors like **trust, coordination, shared situation awareness, and even etiquette** become relevant [88] [89].

An area of focus is **decision authority and autonomy levels** in human-AI interaction. Borrowing concepts from human–automation interaction, researchers outline different modes: sometimes the human is "on-the-loop" supervising AI (which might take the first action unless vetoed), other times AI is "advisory" and human makes final decisions. The optimal mode can depend on context and risk – for high stakes, keeping a human final say is common. However, if AI operates too autonomously without informing the human, it can lead to surprises and loss of trust (as seen in some aviation automation incidents). Therefore, current best practice is ensuring **human override and meaningful control** are always possible, even if the AI is highly autonomous, and designing the AI to *know when to hand control back*. For example, a semi-autonomous drone might fly itself but will ask a human operator for confirmation if it encounters an unexpected situation. These handoff points are essentially the "teaming moments" where coordination is critical.

Human–AI teaming research also heavily involves **user training and mental readiness**. Just as human teams train to work together, humans may need training to work effectively with AI systems – understanding strengths/weaknesses of the AI, how to interpret its outputs, etc. Some recent studies showed that when users received a short training on an AI decision aid's error tendencies, their overall performance improved because they could double-check the AI in its weak areas. This implies that successful human-AI teams might require ongoing learning on both sides (humans learn the AI, AI learns the human's preferences). The emerging field of **machine learning personalization** is relevant: AI systems adapting to individual user behavior over time can improve teamwork (e.g. a smart assistant learning a user's communication style and adjusting).

In terms of applications driving these studies: we see human–AI teaming in **defense (e.g. human-drone teams), healthcare (AI assisting diagnostics or surgery), customer service (chatbots + human agents), manufacturing (human-robot collaboration)**, and many other areas. Each brings specific demands – e.g. a human pilot and AI copilot in a fighter jet need extremely fast, reliable coordination, whereas a physician and diagnostic AI need deep explanation and trust over longer times. Across these, common HF measures of success include *team performance metrics* (speed, accuracy of decisions), *human workload*, *situation awareness*, and *trust levels* [90] [91]. Notably, a 2023 scoping review of human-AI teaming found that **trust and team performance** were by far the most frequently discussed outcomes in the literature, underscoring how central those are to the concept [92].

Ethical and regulatory dimensions are beginning to intersect with human–AI teaming. The upcoming EU AI Act, for instance, will require **human oversight for high-risk AI systems**, effectively mandating that a human can supervise and intervene in AI operations [93] [94]. This legal push echoes HF principles about keeping humans in control and informed. Standards and best practice guidelines (e.g. from ISO or IEEE) are in development for human-centered AI design, emphasizing transparency, controllability, and user involvement in AI system life cycles.

In summary, human–AI teaming research (2019–2024) is working toward a vision where **AI systems are collaborative partners** that enhance human decision-making without eroding human authority or understanding. Key innovations include interfaces for AI explanations, frameworks for sharing task context between human and AI, and dynamic trust calibration mechanisms. But challenges remain, such as preventing **automation bias** (blindly following AI) while also avoiding user overload from too much AI information. The consensus in the HF community is that realizing effective human-AI teams requires a *socio-technical approach*: not only better AI algorithms, but careful design of interactions, user training, and organizational policies that together enable humans and AI to complement each other's strengths [95] [96].

Summary of Key Trends by Domain

The table below provides a high-level summary of notable human factors trends and developments in the last five years, organized by domain:

Domain	Recent Human Factors Trends & Developments (2019–2024)
Aviation & Aerospace	- **Advanced automation & autonomy:** Integration of UAVs and highly automated systems is redefining roles (e.g. single-pilot operations, remote supervisors). Emphasis on keeping humans *in the loop* to avoid "automation surprises" [8] and skill degradation. - **Trust and transparency:** Need for better pilot understanding of AI/automation decisions. Training and interfaces target *trust calibration* so that pilots neither over-rely nor under-utilize autopilot systems [9] [87] . - **Data-driven safety:** Use of big data, real-time analytics, and ML for safety management. Human factors work ensures these tools have human-centered visualizations and support decision-making (in line with **resilience engineering** to anticipate and mitigate risks) [11] [19] . - **Physiological monitoring:** Adoption of wearables and sensors to monitor pilot workload, fatigue, and stress in-flight, with ML algorithms helping predict performance degradation [97] [13] .
Healthcare & Medical	- **AI in clinical workflow:** Rapid growth of AI decision support (diagnosis, triage, etc.) has spurred research on *user-centric AI* – focusing on usability, user trust, and ethics. Ensuring clinicians understand and appropriately trust AI recommendations is a prime concern [21] [22] . - **Telehealth & mHealth usability:** Explosion of telemedicine, remote monitoring, and health apps during COVID-19. HF studies address video consultation fatigue, device usability for patients, data privacy, and integration of remote data into care processes [24] [25] . - **Systems approach to safety:** Widening scope from individual device usability to *macro ergonomics* – using models like SEIPS to improve patient safety at system levels (team communication, organizational culture) [28] [29] . Human factors interventions now target workflow redesign and safety culture alongside UI improvements. - **VR/AR and simulation:** Use of VR for surgical and emergency training, and AR for guiding procedures (and patient education). These innovations show improved engagement and outcomes, while research ensures they meet usability and safety requirements [32] [33] .
Automotive & Autonomous	- **Human–Automation interaction:** Focus on Level 2–3 vehicle interfaces – *handover alerts*, driver monitoring, and shared control. Recent regulations mandate driver drowsiness and distraction monitoring in cars [40] , reflecting HF findings on its importance. - **Trust and driver engagement:** Studies on maintaining appropriate driver trust in ADAS/AVs. Transparent HMIs (displaying sensor status or intent) and driver education help prevent misuse or disuse of automation [42] [43] . Designing for smooth transitions when human control is needed is a key challenge. - **External HMI & pedestrians:** Development of external communication (signals, displays) on AVs to inform pedestrians and cyclists of vehicle intentions. A response to the loss of eye contact in AVs, being refined through HF testing for universally understandable signals. - **Inclusive automotive UI:** Recognition that vehicle HMIs must serve drivers of varying abilities. Recent research on **inclusive design** for shared autonomous vehicles (robo-taxis) emphasizes accessibility (voice controls, simple interfaces) to ensure broad user acceptance [46] [47] .

Domain	Recent Human Factors Trends & Developments (2019–2024)
Human–Computer Interaction	- **AI-enhanced UX:** Interfaces increasingly incorporate AI (recommendation systems, chatbots, voice assistants). HCI research focuses on *explainable and controllable UI* so that users can understand and guide AI behavior [2] [2]. Avoiding user alienation by algorithmic systems is a central theme. - **Natural & immersive interfaces:** Growth in voice, gesture, and AR/VR interfaces. Efforts to improve speech recognition UX and reduce “friction” in conversational UIs. In AR/VR, focus on intuitive interaction techniques and minimizing motion sickness or fatigue for long-term use [52] [53]. - **User well-being & ethics:** Strong push towards designs that support mental health and are free of *dark patterns*. “Zoom fatigue” drew attention to cognitive load in virtual interactions [54] [55], leading to interface adjustments (e.g. less grid gaze, encouraging breaks). Privacy-by-design and inclusive design have become standard considerations (e.g. accessibility guidelines updated, and products evaluated for bias/fairness impacts). - **Remote & data-driven UX methods:** Wider adoption of remote usability testing and analytics. HCI practitioners increasingly use A/B testing, telemetry, and even AI to analyze usability issues. Multi-disciplinary approaches (e.g. mixing psychology and data science) are used to understand complex user behaviors.
Industrial Ergonomics	- **Wearable ergonomics:** Introduction of **exoskeletons** and wearables to reduce physical strain. HF evaluations show potential for injury reduction but emphasize comfort and user acceptance issues (fit, heat, mobility) – requiring iterative, context-driven design [59] [61]. Exosuit adoption is proceeding cautiously, guided by these findings. - **Collaborative robots (cobots):** Increasing use of cobots on assembly lines. HF focus on safety (standards for force limits, etc.) *and* on worker trust and role definition. Studies highlight the need for training and system design that clearly conveys what the robot will do, to avoid confusion or distrust [66] [68]. Psychosocial impacts (job stress, changes in work content) are also being addressed. - **Industry 5.0 – human-centricity:** Emergence of the human-centric manufacturing paradigm (placing worker well-being and empowerment on par with productivity) [72] [73]. This translates to designing interfaces and workplaces that augment workers with AI/analytics (Operator 4.0 concepts) while respecting human limits. HF contributes by ensuring new tech (AR maintenance tools, smart scheduling algorithms) are *user-friendly and supportive* rather than burdensome. - **Data and analytics in safety:** Use of sensor data (wearables measuring posture, fatigue) and analytics to inform ergonomic interventions. Real-time ergonomic monitoring and feedback systems have been piloted, requiring careful design to be helpful and not annoying. Integration of HF in system engineering (digital twins simulating human performance, etc.) allows proactive ergonomic risk assessment in design phases.

Domain	Recent Human Factors Trends & Developments (2019–2024)
Safety-Critical Systems	- **Resilience engineering:** Shift from error elimination to building resilient systems that adapt. Humans are seen as *contributors to safety*, with Safety-II approaches encouraging flexibility and recognizing human expertise as a safeguard [3] [98]. HF research devises ways to measure and train resilience (e.g. scenario-based drills that hone adaptation skills). - **Advanced HMI for control rooms:** Modernization of interfaces in domains like nuclear, aviation ATC, rail, with digital and intelligent systems. Emphasis on **ecological design** and decision support – e.g. visualizing complex process states in intuitive ways, filtering alarms intelligently – to manage operator cognitive load. - **Human–automation teaming in safety roles:** AI-based anomaly detection and decision aids are increasingly deployed (e.g. predictive maintenance alerts). HF ensures these are implemented with human-centered alerting (avoiding overload) and that operators maintain appropriate authority and understanding of automated actions [11] [19]. “Human oversight” is a built-in requirement in emerging safety regulations for AI [93] [94]. - **Human reliability & risk modeling:** More sophisticated human reliability analyses using Bayesian models and simulations are appearing, allowing better incorporation of human factors into overall risk assessments [81] [82]. This dovetails with a trend of integrating HF into **systems engineering** – human factors data and considerations are part of design reviews, hazard analyses, and safety cases more than ever before.
Remote/ Hybrid Work	- **Ergonomics of WFH:** Recognition of widespread home-office issues (improper workstations, extended sitting). Guidance and interventions (ergonomic training, provision of equipment) have been implemented to improve physical setups and habits [84]. Organizations realize their health & safety duty extends to the home setting [99] [100]. - **Mitigating digital fatigue:** Identification of video-call fatigue and “always on” stress. Solutions include encouraging breaks, meeting free times, and technology changes (e.g. less intensive meeting formats) [56]. The importance of *user interface design* in tools like Zoom/Teams for reducing cognitive load is now acknowledged (e.g. interface features to hide self-view or signal participation non-verbally). - **Collaboration tools & practices:** Rapid adoption of collaboration platforms, and the need to make them intuitive and inclusive. HF input has guided improvements like better audio quality (to reduce strain), simpler UX for sharing content, and inclusive features (live captions, chat backchannels) to ensure remote participants can engage equally. - **Boundary management and well-being:** Companies and HF professionals are developing practices/policies to prevent burnout – e.g. **“right to disconnect”** policies, no-email norms after hours, and training managers to support remote team members. Research continues on balancing productivity with mental health in hybrid arrangements, with employee feedback loops increasingly used to fine-tune remote work strategies.

Each domain therefore exhibits unique developments, but common threads across all include the **impact of AI and automation**, a shift towards **human-centered design and resilience**, and the influence of global changes like the pandemic on work and safety practices. Human factors research from 2019 to 2024 has been highly responsive to these trends – expanding its toolkit (e.g. using data science, remote evaluation methods) and reinforcing its core mission of aligning systems with human needs and capabilities.

Conclusion

In the past five years, human factors research has advanced on many fronts, driven by rapid technological innovations and transformative global events. Across aviation, healthcare, transportation, industry, and beyond, the role of the human is being re-examined in light of smarter machines and new ways of working. A unifying insight is that *technology must be designed around people, not vice versa*: whether it's a pilot interacting with an AI autopilot, a doctor using a decision support tool, or an office worker collaborating remotely, the best outcomes occur when systems account for human strengths, limitations, and context [1] [77]. This human-centered philosophy is evident in emerging research themes like explainable AI, workload-adaptive interfaces, and resilience engineering for safety-critical operations.

Key innovations – from wearable exoskeletons and collaborative robots to AR/VR training and voice-based assistants – hold great promise, but also bring new challenges in usability, trust, and integration. Human factors experts have been at the forefront of evaluating these technologies in context and guiding their refinement. Methodologically, the field has embraced both **user-centric qualitative methods and quantitative data analytics**, reflecting a shift to blend classic ergonomic studies with big data and simulation to tackle complex issues. We also see human factors increasingly influencing standards and regulations, as policymakers recognize that accounting for the human element is essential to safe and effective technology adoption (e.g. mandates on driver monitoring, or upcoming requirements for human oversight in AI systems).

Trends in human error, usability, trust, and cognitive load underscore a nuanced understanding: rather than seeking to eliminate "human error" in a vacuum, organizations aim to **design systems that are error-tolerant and that support human cognition and decision-making** under realistic conditions [3] [75]. For example, reducing cognitive load isn't just about training individuals better, but about streamlining interfaces and workflows so that unnecessary complexity is removed. Building *user trust* in automation isn't only a user attitude problem, but a design problem – requiring transparency and reliability in the automation's behavior.

The last five years have also taught the human factors community the value of adaptability. The COVID-19 pandemic forced rapid adjustments in where and how work is done, and HF practitioners responded with research and guidance to maintain performance and well-being under unprecedented circumstances. Similarly, as AI capabilities evolve almost yearly, human factors research continuously investigates how to ensure these tools remain **tools for people** – empowering rather than impairing. Human–AI teaming, perhaps the defining challenge of this era, exemplifies the need for a collaborative future where neither human nor machine is an afterthought, but rather both are designed to work in concert.

In conclusion, human factors research around the world is more relevant than ever, contributing critical knowledge to make complex systems **safer, more efficient, and more user-friendly**. By prioritizing human needs and characteristics – from physical ergonomics to cognitive and emotional factors – recent advances across domains point towards a future in which technology and environments are better tuned to how people actually work, think, and thrive [20] [2]. The ongoing integration of human factors with fields like data science, AI development, and systems engineering will further ensure that as innovation accelerates, the "human touch" is not lost but rather systematically incorporated into design and policy. The result will be systems that not only achieve technical performance, but also uphold human dignity, health, and productivity in the many domains of modern life.

Sources: The analysis above draws on a range of recent research findings, review articles, and industry/regulatory reports, including but not limited to: HFES and other conference proceedings; systematic reviews in healthcare informatics [20] [21]; NASA technical papers on aviation safety and autonomy [9]; studies on driver automation interaction [40]; HCI grand challenges summaries [49] [2]; ergonomic evaluations of exoskeletons [59]; human–AI teaming reviews [44] [88]; and evaluations of remote work effects [84] [54], among others as cited throughout this report. These sources provide a foundation for understanding the state-of-the-art human factors developments from roughly 2019 through 2024, illustrating both the progress made and the ongoing efforts to address new challenges in the interaction between humans and complex systems.

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