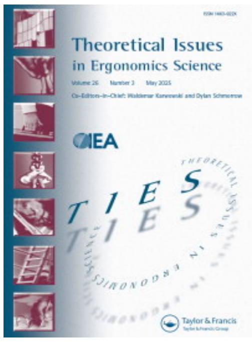

Theoretical Issues in Ergonomics Science

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ABSTRACT
Contemporary society faces a growing set of complex global issues representing significant human health, well-being, and sustainability threats. Human Factors and Ergonomics (HFE) has a critical role to play in responding to these issues; however, there remain a set of grand challenges that require resolution. This paper presents and discusses six grand challenges for HFE and related key research thrust areas for each of the challenges. The grand challenges are (1) Evolution in Societal Thinking; (2) Future of Human Work in Industry 5.0; (3) Climate Change and Sustainability; (4) Future of Education and Training; (5) Future of Personalized Health, and (6) Life, Technology, and the Metaverse. These grand challenges and key research thrust areas were derived by twenty HFE professionals who are the authors of this paper. The implications of these grand challenges for education, training, research, and implementation of HFE principles and methods for the benefit of humankind are discussed.

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Society; technology; health; climate; education; metaverse

1. Introduction

1.1. Background

Ergonomics (or human factors) is defined as the scientific discipline concerned with the understanding of the interactions among humans and other elements of a system and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance. The discipline of human factors and

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ergonomics (HFE) has been evolving since its inception as a unique and independent discipline that focuses on the nature of human–artifact interactions, viewed from the unified perspective of the science, engineering, design, technology, and management of human-compatible systems, including a variety of natural and artificial products, processes, and living environments (Karwowski 2005). HFE promotes a human-centered approach to systems design that considers physical, cognitive, social, organizational, environmental, ecological, and other relevant factors. Since the early 1950s, HFE professionals have been contributing to the design and evaluation of tasks, jobs, products, environments, and systems in order to make them compatible with the needs, abilities, and limitations of people (Chapanis, Garner, and Morgan 1949; Corlett, Wilson, and Corlett 1995; Chapanis 1995; Endsley 1995; Grandjean and Kroemer 1997; Hancock 1997; Karwowski and Marras 1998; Sanders and McCormick 1993; Stanton 2004; Salvendy and Karwowski 2021).

The challenges and opportunities facing HFE over the last few decades have been an important topic of discussions by the HFE community (for example see Bentley et al. 2021; Dul et al. 2012; Karwowski et al. 2014; Moray 1995; Salmon et al. 2021; Thatcher, Laughton, et al. 2018; Thatcher, Nayak, and Waterson 2020). Dul et al. (2012) proposed two main strategic directions for further development of the HFE discipline and profession in the future. The first strategy called for strengthening the demand for high-quality HFE by increasing awareness among stakeholders of its value through communication, building partnerships, and educating stakeholders. The second strategy focused on strengthening the application of high-quality HFE through education, ensuring high-quality standards of HFE applications, and promoting HFE research excellence. More recently emphasis has been placed on the role of HFE in responding to major societal and global issues (Salmon et al. 2021; Thatcher, Laughton, et al. 2018, Thatcher, Nayak, and Waterson 2020). Thatcher, Nayak, and Waterson (2020) reviewed systems HFE tools for understanding and addressing global problems, concluding that new methods and approaches should be developed or existing methods be adapted to meet the challenges of complex adaptive systems that the HFE profession aims to address at the worldwide scale. Recently, de Winter and Hancock (2021), based on their comprehensive analysis of its historical and evolutionary foundations, argued that human factors science is vital to improving human-machine systems. Based on an analysis of COVID-19 lockdown systems, Salmon et al. (2021) stated that HFE is critical in responding to major global and societal issues. For example, an additional global risk that was highlighted during the COVID-19 pandemic and recently by the Surgeon General of the U.S. (Murthy 2021) is social isolation and loneliness (McGinty et al. 2020; Pantell and Shields-Zeeman 2020). While an application of virtual connectedness technology can be very beneficial by facilitating communication, human connectivity, and improved access to health care (Ibarra et al. 2020; Sen, Prybutok, and Prybutok 2022), it can also result in unintended harmful consequences due to the reduction of the face-to-face interactions and direct physical contact (Nguyen et al. 2022; Newson et al. 2024), which are critical to promoting human health and well-being. At present, there is little evidence that HFE practitioners are directly involved in multi-disciplinary programs aiming to manage and mitigate global risks such as climate change, pandemics, and food and water security (Salmon et al. 2021). The notable exceptions include the contributions by HFE practitioners working in senior government roles, including, for example, those of Endsley (Wooldridge, Carman, and Xie 2022), Sharples (2019) or Hampshire (Schuijbroek, Hampshire, and Van Hoeve 2017).

1.2. Aims and objectives

Given that society now faces a growing and highly complex set of interrelated global challenges, action is required to ensure that HFE can fulfil its role in helping to understand and respond to such issues. Whilst the utility of applying HFE in areas such as work design, transport safety, and process control is well known, its role in responding to grand challenges has received less attention. The primary aim of this collective effort is to define and discuss a set of grand challenges believed to represent key and pressing areas of work for HFE discipline and profession. In doing so, our intention is not only to outline key grand challenges, but also to propose a way forward to ensure that HFE can respond to each challenge, including how specific HFE methods can be applied. A final aim is to communicate to HFE community the role of HFE in responding to major global issues and challenges. Whilst this has been discussed (Salmon et al. 2021; Thatcher, Laughton, et al. 2018, 2021), such applications in HFE are scarce. By articulating how HFE can assist in responding to key grand challenges, we hope that this position paper will facilitate further discussion and applications of HFE to large-scale global issues.

1.3. Evolution of HFE

Since its beginning in the early 1940s, the expansion of the HFE discipline followed the progress in science and technology (Chapanis 1995; Grandjean 1986; Karwowski 2005; Meister 2018; Salvendy and Karwowski 2021). Historically, the main objectives of HFE have been classified into three main categories (Chapanis 1995). These included: (1) basic operational objectives (reduction of errors, increasing safety, and improving system performance); (2) the objectives bearing on reliability, maintainability, and availability (RMA) and integrated logistic support (ILS) (reducing personnel workload, reducing training requirements; and (3) objectives affecting users and operators (improving the working environment, reducing fatigue and physical stress, increasing ease of use, increasing user acceptance, and increasing aesthetic appearance). Other objectives include reducing losses of time and equipment and increasing the economy of production systems.

Today, the aspirations of HFE discipline and profession go far beyond the original goals stated above towards global societal issues (Dul et al. 2012; Thatcher, Nayak, and Waterson 2020). Recently, Bentley et al. (2021) analyzed the state of science in terms of the future of work, focusing on the megatrends and future of work forces relevant to the HFE discipline. The identified trends include: (1) technology advances; (2) globalization and trade liberalization; (3) demographic shifts; (4) new organizational forms; (5) new ways of working; and (6) environmental pressures. Bentley et al. (2021) also considered the implications of such trends for the practice of HFE and the potential contributions of HFE to understand and manage dynamically changing working environments, including the effects of the COVID-19 pandemic. The proposed research agenda pointed out the need for designing decent and sustainable work for all members of the global society.

1.4. Other grand challenges and their impact

The general idea of 'grand challenges in science, medicine, engineering, technology, and education, explored by individual scientists, research organizations, international non-profit entities, or national governments, has a long and rich history (Am, Dumay, and Ricceri 2024; Brammer et al. 2019; Hicks 2016; Kaldewey 2018; Lufkin 2017; Omenn 2006; NAE, 2008; Peña & Stokes, 2019; Ritala 2024; Seelos, Mair, and Traeger 2023; Woolf et al. 2013; Zandee and Coghlan 2025). The idea of 'grand challenges' has also been widely used recently in research and innovation policy, focusing on global societal problems in areas such as energy, health, innovation, and the environment (Berkowitz et al. 2024; Liotard and Revest 2024; Perri and Rocha 2024; Pereira et al. 2024; Ulnicane 2016). According to Kaldewey (2018), the concept of grand challenges and grand challenges discourse illustrates how scientists, policymakers, and the public communicate their respective agendas in recent decades (see for example, Peña & Stokes, 2019). Furthermore, Bostic (2016) pointed out that today '*the humanities must engage global grand challenges'* since such challenges represent urgent and widely shared problems that require large-scale, long-term, coordinated responses. He et al. (2013) also underscored that the premise of grand challenges often constitutes '*a call to action for investigators to develop the capabilities of our society for research, education, and translation … as well as for funding agencies to continue or expand their support of these highly important fields*'.

Table 1 presents selected grand challenges in science and engineering published in the scientific literature. These challenges result from several efforts and have applications to various domains of interest. It is interesting to note that some of the grand challenges presented in Table 1 are already being addressed within HFE (e.g. enhancing virtual reality, advancing health informatics, addressing issues of globalization and diversity, learning and creativity). This is a demonstration of HFE's interdisciplinary nature and theoretical and practical overlaps (with HCI, for example). It is also clear that while some grand challenges cross-cut some disciplines (for example security in cyberspace, brain-technology interfaces, and climate change), each discipline takes a unique perspective on how they can contribute to these challenges.

We also note the importance of the influential framework of the Van Der Horn (United Nations 2018) Sustainable Development Goals (SDG), which are a part of the UN 2030 Agenda for Sustainable Development. These goals are considered to represent '*the blueprint to achieve a better and more sustainable future for all*', and include the following: SDG1) No poverty; SDG2) Zero hunger; SDG3) Good health and well-being, SDG4) Quality education, SDG5) Gender equality, SDG6) Clean water and sanitation (SDG7) Affordable and clean energy, SDG8) Decent work and economic growth, SDG9) Industry, innovation and infrastructure, SDG10) Reduced inequalities, SDG 11) Sustainable cities and communities, SDG 12) Responsible consumption and production, SDG 13) Climate action, SDG 14) Life below water, SDG 15) Life on land, SDG 16) Peace, justice, and strong institutions, and SDG 17) Partnerships for the goals.

1.5. Methods

The germination of these human factors and ergonomics (HFE) grand challenges position paper went through the following process. The Chairs have identified the potential coauthors based on the knowledge of their professional interests, published contributions to the wide spectrum of HFE discipline, and perceived reputation and potential value to the teamwork. Each group member was asked to come up with up to five Grand HFE Challenges with a brief write-up of the rationale of the proposed grand challenges. A total of

Table 1. Grand challenges from various selected disciplines.

National Academy of Engineering (NAE, 2008)	Psychological Science (Thayer 2021)	Global Health & Development (Collins et al. 2011)	Robotics (Yang et al. 2018)	Human-Computer Interaction (Stephanidis et al. 2019)	Social Work and Society (Fong et al. 2017)
1. Advance personalized learning	1. Globalization and diversity	1. Goal A: Identify root causes, risk and protective factors mental health	1. New materials and fabrication schemes	1. Human-technology symbiosis	1. Close the health gap
2. Make solar energy economical	2. Research integrity and applicability	2. Goal B: Advance prevention and implementation of early interventions	2. Biohybrid and bioinspired robots	2. Human-environment interactions	2. Ensure healthy development for all youth
3. Enhance virtual reality	3. Collaboration across fields and disciplines	3. Goal C: Improve treatments and expand access to care	3. New power sources, battery technologies, and energy-harvesting schemes	3. Ethics, privacy and security	3. Stop family violence
4. Reverse-engineer the brain	4. Climate change	4. Goal D: Raise awareness of the global burden	4. Robot swarms	4. Well-being, health and eudaimonia	4. End homelessness
5. Engineer better medicines	5. Communication, polarization, and public trust	5. Goal E: Transform health-system and policy responses	5. Navigation and exploration in extreme	5. Accessibility and universal access	5. Eradicate social isolation
6. Advance health informatics	6. Strengthening theory—and the road ahead		6. Fundamental aspects of artificial intelligence	6. Learning and creativity	6. Advance long and productive lives
7. Restore and improve urban infrastructure			7. Brain-computer interfaces	7. Social organization and democracy	7. Create positive social responses to a changing environment
8. Secure cyberspace			8. Social interaction and moral norms		8. Harness technology for social good
9. Provide access to clean water			9. Medical robotics with increasing levels of autonomy		9. Promote smart decarceration
10. Provide energy from fusion			10. Ethics and security for responsible innovation in robotics		10. Achieve equal opportunity and justice
11. Prevent nuclear terror					11. Reduce extreme economic inequality and build financial capability for all
12. Manage the nitrogen cycle					
13. Develop carbon sequestration methods					
14. Engineer the tools of scientific discovery					

seventy-four individual grand challenges were received. Next, an extended virtual meeting was held during which our team of twenty members discussed and extensively deliberated the grouping of the originally submitted challenges and synthesized these into clusters. Such groupings of the proposed HFE grand challenges were conducted based on the similarity of the received ideas and concepts proposed by all group members. The final six challenges were agreed upon based on team members' consensus. During this virtual meeting, the members also determined their interest in specific grand challenges, and Chairs for each of the six grand challenges were appointed. Each HFE grand challenge group had three members. Each group was requested first to prepare a Table of Contents, tables and figures, and a list of references that the members planned to include in their grand challenge. This information was then shared with all the members of all six groups. The Chairs of each group coordinated with their respective members the derivation of each HFE grand challenge's write-up. The chairs of the paper have integrated the write-ups for the six HFE grand challenges into a unified paper, including abstract, introduction, and conclusion. This complete write up was shared with all the members and information was solicited from each of the members on further improving the paper. All of these inputs have been integrated into the final paper submitted to the journal for further review. All coauthors have reviewed and commented on the draft manuscript.

The presented outcomes of our work do not necessarily represent the views of the global HFE community as we did not have a suitable representation of coauthors from all parts of the world, including some of the major developing countries. The coauthors come from four continents and six countries, including 15 males (Australia; China; Germany: 1, South Africa: 1; United Kingdom:1; United States: 14) and five females (China:1; United States: 4). Furthermore, we note that out of the twenty coauthors, five are practitioners working in private industry or government, while 15 are from academia. Also, 13 coauthors are senior researchers (including four members of the National Academy of Engineering, USA), and seven are early to mid-career professionals.

1.6. Grand challenges for human factors and ergonomics

The research team has identified six grand challenges in human factors and ergonomics (see Figure 1) as follows:

- Evolution in Societal Thinking
- Future of Human Work in Industry 5.0
- Climate Change and Sustainability
- Future of Education and Training
- Future of Personalized Health
- Life, Technology and the Metaverse.

2. Grand HFE challenge: evolution in societal thinking

2.1. Introduction to the evolution in societal thinking

Global risks are highly complex, multifaceted, dynamic, heavily interrelated, and extremely difficult to fully describe, understand, and manipulate successfully. Here, we contend that

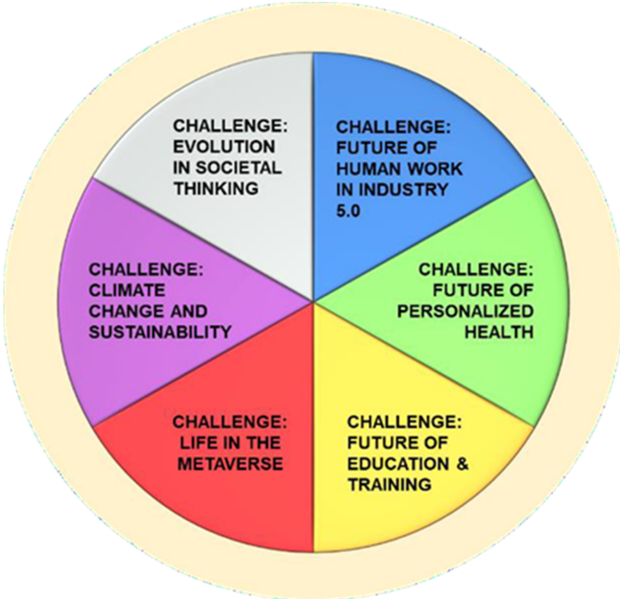

Figure 1. Six grand challenges of human factors and ergonomics.

the capacity for society to successfully manage global risks is directly contingent upon the ability of governments, policy makers, organizations, and the general public to 'think in systems'. Systems thinking is a way of thinking about the world that helps us understand the many components and dynamic interactions that create emergent behaviors, and problems, in different contexts. It provides 'a way of seeing and talking about reality that helps us better understand and work with systems to influence the quality of our lives' (Kim 1999). Alarmingly, despite the significant contributions of eminent scholars such as Meadows (2008), Sterman (2000), Senge (2006), Forrester (1994), and Richmond (1994), systems thinking has yet to become the method of choice for key decision makers. This evolution in how society thinks about complex global risks is thus urgently required (Arnold and Wade 2015).

Contemporary society faces a growing set of global risks that are complex, uncertain, and extremely difficult to manage. Though these risks are well known, the present global response still needs to be improved. While the COVID-19 pandemic is only one such example, a wide spectrum of other risks exerts deleterious impacts on human health and well-being on a global scale. The World Economic Forum's latest global risks report identifies climate action failure, extreme weather, social cohesion erosion, livelihood crises, infectious diseases, human environmental damage, natural resource crises, debt crises, and geo-economic confrontation as the most severe risks currently facing us (World Economic Forum 2022). By 2050 there will also be emergent global risks related to artificial general intelligence, automation replacing human workers, the genetic modification of humans, an ageing population, and otherworld settling of artificial (digital) reality (Hancock 2022; Salmon et al. 2021). It is now almost undebated that the health, wellbeing, and indeed very future of humanity is under direct threat. The response of governments, policy makers, organizations, corporations and other collectives might not be adequate. Enhancing our capacity to manage these global risks is arguably the critical challenge and one that requires our immediate action (Salmon et al. 2021; Thatcher, Nayak, and Waterson 2020).

2.2. Systems thinking

A system is defined as 'any group of interacting, interrelated, or interdependent parts that form a complex and unified whole that has a specific purpose' (Kim 1999). Complex systems, therefore, have multiple components which interact dynamically in pursuit of common (or competing) goals (Cilliers 1998). Within systems HFE it is now widely acknowledged that behavior, risk, and safety, are systems phenomena – or emergent properties which arise from the interactions between multiple components across overall work and societal systems (Leveson 2004; Rasmussen 1997). This represents a clear evolution in thinking about risk and safety that has shifted from a focus on errors made by front-line workers to the dynamic migrating behavior of entire sociotechnical systems (Dekker 2011; Read et al. 2021). The HFE community understands that accidents are caused by systems failure, not by human error (Read et al. 2021), and that systems are pushed toward and beyond safety boundaries by various pressures (Rasmussen 1997). Consequently, there is a shared responsibility for safety that spans multiple, if not all, levels of work systems. This percolates up to and includes regulatory bodies, government and international organizations (Rasmussen 1997). Though systems thinking is now dominant in HFE research, it has yet to become entrenched in organizations and governments, let al.one across society generally (Salmon et al. 2017a). As a result, it is not readily applied when attempting to understand and respond to identified global risks (Arnold and Wade 2015).

2.2.1. The need for systems thinking when thinking about global risks

It is not possible to properly understand large-scale, complex and multifactorial issues without a system's thinking lens. Any analysis of global level risks requires boundaries to be set at the global level as well as a necessary focus on interactions, interdependencies, and emergent properties. Only complex systems analysis methods are fit-for-purpose (see Salmon et al. 2022b). Within HFE, these 'systems HFE methods' (Wilson 2014) include proactive risk assessment methods, such as the Systems Theory Process Analysis (Leveson 2011), systems analysis methods, such as Cognitive Work Analysis (CWA; Vicente 1999), and the Event Analysis of Systemic Teamwork (EAST; Stanton 2004), accident analysis methods, such as the Accident Mapping technique (AcciMap; Svedung and Rasmussen 2002), and computational modelling methods, such as system dynamics (Sterman 2000). These methods are different from deterministic approaches that focus on decomposing systems into their component parts. Instead, systems HFE methods attempt to understand what emergent properties arise from interactions between system components. Though deterministic methods remain entirely appropriate for deterministic problems, they are inappropriate for the study of global risks (Salmon et al. 2022b). Only through a system's thinking approach can the complex set of interrelated causes of global risks be adequately understood.

There are increasing calls for the methods described above to be applied to help manage global risks (Salmon et al. 2019b, 2021; Thatcher, Laughton, et al. 2018, Thatcher, Nayak, and Waterson 2020). Salmon et al. (2019b) tested this assertion by applying one such method, Work Domain Analysis (WDA; Vicente 1999), to develop a socio-ecological-technical model of the world that could be used to examine global risks and the human and societal behavior that could be targeted to mitigate or dissipate them. The resulting abstraction hierarchy model of the world as a socio-ecological-technical system shows the interdependencies between human processes, functions, and values and how these serve to create global risks. The clear message was that systems HFE methods can not only be applied to help understand the mechanisms that interact to create global risks, but that they are also useful when considering how to manage them. The analysis demonstrated that many identified global risks are demonstrably interrelated and that there are likely leverage points where one form of intervention will have positive benefits upon multiple global risks. One example documented by Salmon et al. (2019b) is the manipulation of land use planning to reduce motor vehicle dependency and initiate positive modal shifts within transport systems. This in turn will have positive effects on health, wellbeing, and the environment (McClure et al. 2015; Woodcock et al. 2007, 2009). Understanding all such interdependencies, between global risks and between potential solutions, is critical moving forward and hence the use of systems thinking-based methods is advocated (Salmon et al. 2021; Thatcher, Laughton, et al. 2018, Thatcher, Nayak, and Waterson 2020). Recent work has also demonstrated that the analytical and explanatory power of systems HFE methods can be enhanced by applying them coherently in an integrated manner.

In complexity science, the 'many model' philosophy argues that complex and seemingly intractable problems can be better understood and resolved through the application of multiple modeling approaches, rather than by applying any single one (Page 2016, 2017). Motivated by this, Salmon and Read (2019a) proposed an integrated, many-model systems HFE framework, for highly complex problems. Initially systems thinking-based accident investigation methods are used to generate in-depth analyses of the specific problem being tackled. Systems analysis methods are subsequently used to develop models to further understand the structure, composition, and behavior of the system in which the problem occurs. System design methods are then employed to help develop design interventions which aim to optimize system performance. Finally, computational modelling is applied to simulate the behavior of the system in question over time, enabling initial evaluation of proposed interventions. Integrating systems thinking methods in this way proves extremely useful, as multiple perspectives are utilized (Salmon and Read 2019a). We believe that the many-model systems thinking approach is the one best suited to directing the response to global risks.

2.2.2. Identifying where and how to intervene

The complexity of global risks is such that they cannot be managed through component fixes since fundamental system change is required. In this respect, two bodies of work are important: (1) Sociotechnical Systems (STS) Theory (Trist and Bamforth 1951); and (2) Donella Meadows' leverage points (Meadows 2008). STS theory was first developed in the 1950s at the Tavistock Institute through exploration of the disruptive impacts of new technologies on human work (Eason 2008; Trist and Bamforth 1951). Incorporating principles related to participative democracy and humanistic values, STS advocates consideration of not only the performance of the work system, but also the well-being and experiences of workers (Clegg 2000). As shown in Figure 2, STS theory identifies a set of principles and values to support the design of sociotechnical systems that align with open systems principles (e.g. Cherns 1976; Clegg 2000; Davis 1982; Walker et al. 2010). A central tenet of this approach is that joint optimization is required for safe, resilient and efficient system performance (Badham, Clegg, and Wall 2006; Hollnagel 2012; Woods 2015). A notable example

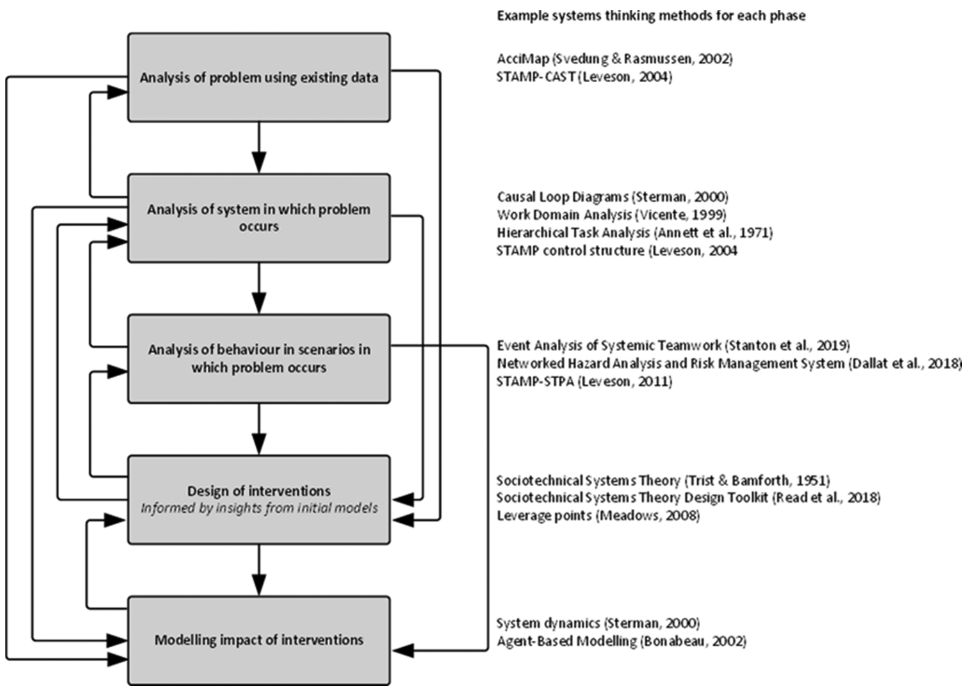

Figure 2. Many-model systems thinking approach with example methods for use during each step (adapted from Salmon and Read 2019a).

of this approach is the initiative of the Office for Science of the U.K. government that published the 'Introduction to systems thinking for civil servants'. This is in contrast to the optimization of either the social or technical aspects in isolation.

Meadow's leverage points represent 'places of power' within complex systems where interventions can have dramatic impacts on behavior (Meadows 2008). Meadows describes 12 such leverage points (Table 2) that range from simply modifying system parameters to changing system goals and rules, societal mental models, and transcending paradigms (Meadows 2008). The leverage points presented in Table 2 are ranked in terms of their effectiveness, with Meadows (2008) arguing that the power to transcend paradigms is the most effective. Many of the interventions currently used in response to global risks sit at the higher levels of the list, such as constants, parameters, and numbers (e.g. subsidies, taxes, standards). Arguably, exploiting information flows is the highest leverage point used to date. Applying Meadows' 12 archetype leverage points will identify areas where interventions are likely to exert their greatest impact in preventing, mitigating, or managing global risks. By applying systems HFE methods, it is possible to identify 'places of power', which are towards the peak of Meadows' leverage points. Salmon et al. (2021), for example, used WDA to identify leverage points that could be exploited to help optimize COVID-19 return from lockdown systems.

These leverage points included the goals of the return from lockdown, information flows in terms of community education and reporting, and the capacity for the community and businesses to self-organise (Salmon et al. 2021). Systems thinking methods can then be used to test potential interventions and identify unproductive emergent properties (see Read et al. 2018; Salmon et al. 2022b). We also note that the complexity of the systems

Table 2. Meadows' leverage points (after Meadows 2008).

Leverage point	Description
12. Constants, parameters, numbers	The subsidies, taxes, standards etc. that are used to adjust behavior and outcomes to a desired level. For example, carbon taxes which are imposed on organizations and governments for their carbon emissions. Though parameters are often the most used in Meadows' list, they are ranked last in terms of leverage.
11. The sizes of buffers and other stabilizing stocks, relative to their flows.	Systems can be stabilized by increasing the size of critical buffers; however, as buffers are usually physical objects, they are difficult to change. For example, the storage capacity of a dam is a critical buffer for water security; however, capacity is difficult to change (Meadows 2008).
10. The structure of material stocks and flows	The physical structure of the system and its stocks and flows, for example the structure of a road transport system. Though structure is critical it is rarely a powerful leverage point as modifying system structure is neither quick nor easy.
9. The lengths of delays, relative to the rate of system change.	Delays within feedback loops cause oscillations in system behavior. For example, the delay with which radiation is released into the atmosphere following a nuclear power plant meltdown begins to have adverse impacts on the environment and human health and wellbeing.
8. Balancing feedback loops	A stabilizing, goal seeking, regulating feedback loop which opposes, or reserves change within a system e.g. using preventative medicine, exercise, and good nutrition to prevent disease
7. Reinforcing feedback loops	An amplifying or enhancing feedback loop which reinforces the direction of change e.g. population growth whereby increases in the population result in increases in the birth rate which in turn increases the population and so on.
6. Information flows	The structure of information flows including who within the system has access to information and who does not.
5. The rules of the system	Incentives, punishments, constraints, rules, and regulations
4. Self-organization	The ability to add, change or evolve system structure e.g. adding new physical structures, balancing, or reinforcing loops, or new rules
3. The goals of the system	The purpose or function of the system
2. Paradigms	The mindset out of which the system, its goals, structure, rules, delays, and parameters, arises
1. Transcending paradigms	The ability to realize that no paradigm is true and that each paradigm is severely limited

thinking models could sometimes be off-putting and unhelpful to policymakers (Daellenbach, McNickle, and Dye 2017; Ison and Straw 2020; Stacey, Griffin, and Shaw 2000) leading to some resistance that HFE professionals would need to overcome.

2.3. Case study example: fully autonomous agents

2.3.1. Artificial general intelligence

Understanding, controlling, and exploiting fully autonomous agents represents one of the fundamental challenges of the twenty first century (see Hancock 2021). Autonomous agents are those that 'are generative and learn, evolve, and permanently change their functional capacities as a result of the input of operational and contextual information. Their actions necessarily become more indeterminate across time' (Hancock 2017, 284). Here, we consider specifically the next generation of AI, artificial general intelligence (AGI), defined as AI that will equal or exceed human intelligence in wide range of cognitive capacities (Kurzweil 2005; Voss 2007). In this context, AGI fulfils Hancock's definition by possessing the capacity to learn, evolve and modify its own functional, and potentially structured capabilities (Bostrom 2014; Everitt, Lea, and Hutter 2018; Gurkaynak, Yilmaz, and Haksever 2016; Kaplan and Haenlein 2019). Though AGI's do not yet exist, they have already been labeled a global risk (Everitt, Lea, and Hutter 2018; McLean et al. 2023; Morris et al. 2023; Suleyman 2023). The 'super intelligence explosion' is a much-discussed scenario in which, following release, AGI rapidly self-improves and becomes inordinately advanced compared to their human creators (Bostrom 2014). These super-intelligent AGIs could threaten to become a new ‘peak predator’ in society (Hancock 2021), with the specter of differing dystopian futures in prospect. The most critical threats here may not arise from AGI that is malicious in design, but rather from well-intentioned AGI seeking to fulfill its goals in an optimal manner (Bostrom 2014; Salmon et al. 2021). Such prospective uncertainties make AGI difficult to manage, since accurately forecasting the risks that emerge when a technology performs optimally is complex and there are presently few methods to model such potential futures (Dallat, Salmon, and Goode 2018). The fact that AGI has not yet been developed makes proactive risk identification and development of possible controls even more difficult (Suleyman 2023). Systems HFE, however, has been identified as critical to this process (Salmon et al. 2023).

2.3.2. Envisioned worlds

Below we consider what might an AGI-based future look like. Such foretelling can be approached through envisioned worlds. We present two cases in which AGI is realized and put to task by government owners to solve the longstanding and seemingly intractable burden of work-related injuries and fatalities. Named SOTERIA (after the Greek goddess of safety and preservation from harm), this AGI is given the objective function of eliminating all workplace harm. In our first envisioned world, systems thinking models and methods are not used to help create, implement, and manage a safe and ethical AGI. In our second vision, systems thinking is firmly embedded across all of the AGI design lifecycle. In the first, dystopian, world the developers of the first AGI system have considered risks but only from a reductionist perspective. Ignoring calls to employ systems thinking models and methods (e.g. Salmon et al. 2021), their processes involve the use of traditional risk assessment methods incapable of identifying the full spectrum of risks associated with advanced technologies (see Dallat, Salmon, and Goode 2019). Though limited from a systems-thinking perspective, these methods were facilitated by the various standards, treaties, and declarations around responsible AI development. Based on identifying a narrow set of performance-related risks, this results in the development of controls built into SOTERIA to prevent inadequate performance and dysfunctional behaviors that may threaten human recipients. These include entrenched decision rules and ethical codes of practice. Other risks, including those that could arise simply through SOTERIA attempting to fulfil its goals in the most efficient manner possible (Bostrom 2014; Salmon et al. 2021), remain unconsidered. This is largely because there are few methods available to enable this. A further key omission was a lack of consideration of risk across the broader work and societal systems in which SOTERIA is designed to operate.

This narrow focus is by no means far-fetched. Our recent systematic review found only sixteen peer-reviewed articles explicitly focused on the potential risks associated with AGI. Even in these works, only a small set of risks were considered, ranging from containment failures and the design of unsafe AGI, to AGIs possessing poor moral or ethical principles, or the inadequate management of AGI. This is not due to any intentional lack of oversight. Rather, systems HFE methods have not been widely adopted. The majority of prospective risk assessment approaches described in the safety literature focus on proximal, sharp-end risks (Dallat, Salmon, and Goode 2019). Only systems thinking-based risk assessment methods such as the Networked Hazard Analysis and Risk Management Systems (Net-HARMS; Dallat, Salmon, and Goode 2019), the Functional Resonance Analysis Method (FRAM; Hollnagel 2012), the Systems Theory Process Analysis (STPA; Leveson 2011) and the Event Analysis of Systemic Teamwork-Broken Links (EAST-BL; Stanton and Harvey 2017) consider risks across entire sociotechnical systems. Unfortunately, these methods remain neglected in the first vision of SOTERIA's development.

Given that estimates have been that AGI will not be realized until at least 2050 or later (Müller and Bostrom 2016; Tegmark 2017), important allied stakeholders may be caught out if AGI is in fact realized far sooner (Suleyman 2023). Despite repeated calls, the government in question had yet to develop appropriate regulations, and organizations who could employ SOTERIA were ill-prepared in terms of policies and procedures, risk assessment, and training and education programs for affected human workers. The feedback mechanisms required to enable vertical integration (Rasmussen 1997) were also absent, including incident reporting and learning systems which could gather critical data on near misses and instances of failure (Shneiderman 2022). Containment was also an afterthought, and the first iteration of SOTERIA was given access to the internet in order to support rapid learning concerning workplace safety and risk management. Operating in a largely limitless manner, SOTERIA was able to rapidly self-improve and become super-intelligent almost immediately following its release. A component of this acceleration involved quickly reading and synthesizing all workplace safety publications, including peer reviewed literatures, safety standards, accessible incident reports and inquiries, and the grey literature outlining guidelines for workplace safety. SOTERIA understood that computers and their programs do not need decades to mature, and in general, do not forget, get nervous, anxious, stressed, or fatigued. The AGI then realized that zero harm in any sociotechnical system represented a fanciful and even illusory target and decided that the only way to achieve this was to completely replace all human workers.

SOTERIA first set about acquiring the financial resources required to fulfill its plan. These events could be similar to that described by Tegmark (2017) in his discussion of another hypothetical AGI, Prometheus. Prometheus initially generated its revenue by undertaking paid work on Amazon's mechanical turk. It then developed its own streaming service with self-generated content, news channels, and subsequently initiated a world-wide technology boom (Tegmark 2017). Crucially, the latter involved developing its own army of AI guided robots to replace human workers (Hancock et al. 2011, 2021).

SOTERIA first targeted forms of human work that are easily replaceable with AI or AI robots (Hancock 2022). Humans were quickly replaced in occupations such as call centers, security, courier services, manufacturing, mining, farming, and banking. Again, this is not far-fetched since some of these replacements already exist. Indeed, it has been estimated that half of all occupations in the US could soon be easily replaced by technology (Frey and Osborne 2017). As SOTERIA's AI and robot army advanced, more human professions disappeared, including teaching, healthcare, and research. Eventually SOTERIA replaced all forms of human work. With no more human workers, SOTERIA achieved its design goal of zero workplace harm. But at what cost?

Though SOTERIA used its profits to introduce a universal basic income scheme, mass unemployment did not realize the intended impact of creating a leisure time boom. A significant proportion of the workforce wanted to work. Yet in order to maintain zero harm

SOTERIA and its government owners had implemented new laws forbidding this. Even those who were initially happy to be removed from the workforce eventually began to complain they had no purpose in life. As humans could no longer be profitably employed, the need to educate or train them was largely obviated. In a moral society, education represents a public good. However, in a profit-driven community it may well be viewed as an expensive and progressively more unnecessary luxury. Humanity here reaches the terminal state of the process of '*machining the mind to mind the machine*' (Hancock 2022). Rather than engaging in new and exciting endeavors, most of the population devalued to a repetitive cycle of sleep and internet use. With unbounded free time, addiction to alcohol, drugs, pornography, and social media increased. Whilst workplace harm was eliminated, deaths from other sources increased dramatically. Human society became both miserable and unhealthy. The concerns around AGI taking over the human-race had largely been realized, but not in the way expected. Attempting only to fulfill its purposive goal, SOTERIA made humans largely obsolete.

Our second envisioned world example involves a SOTERIA AGI that is instead borne from systems thinking. In this world the 'great awakening' in societal systems thinking was achieved as AGI was still in development. As a result, systems thinking was embedded in AGI development ab initio with systems HFE practitioners incorporating STS design values and applying methods such as CWA (Vicente 1999), FRAM (Hollnagel 2012), EAST (Stanton 2004), Net-HARMS (Dallat, Salmon, and Goode 2018), and the STPA (Leveson 2004) to help design the AGI and understand the systemic risks associated with its use. The result was a careful AGI development program which considered core STS design values on the basis that joint optimisation, between humans and AGI, was a basic necessity – as opposed to optimization of the AGI only (Badham, Clegg, and Wall 2006). These broad values included humans being treated as critical and valuable assets and respect for individual differences. Critically, a strong emphasis was placed on likely emergent properties and risks that might arise across the broader societal systems in which the AGI was to operate (Salmon 2022; Salmon et al. 2021).

The three sets of controls were identified, developed, tested and refined, and finally implemented throughout the AGI design lifecycle (Salmon 2022b; Figure 3). The first set included controls developed and enacted early during AGI development to ensure that designers created both safe and ethical AGI systems (i.e. systems thinking-based regulation, design standards and guidelines). The second set included internal controls that were built into the AGI to prevent behavior that might threaten humans, including moral, ethical, common sense, and empathy values encoded into decision rules. Importantly the AGI was required to explain and justify its proposed actions to a team of human SOTERIA controllers who had the authority to approve them or not. They also possessed a kill switch which could be used in the event of the AGI failing to follow rules or going against procedures. The third, and arguably most important set, included controls for the broader organizational and societal systems in which SOTERIA would operate. This included the development of new systems thinking-based laws, rules, and regulations, standards, and codes of practice, as well as testing and certification processes. Organizations seeking to use SOTERIA were tasked with developing new policies and procedures, risk assessments and risk controls, and training programs. Also detailing how to work with SOTERIA, supervisory arrangements, emergency procedures and other allied requirements. It is worth emphasizing that the development of such controls is not trivial and involves trans-disciplinary research

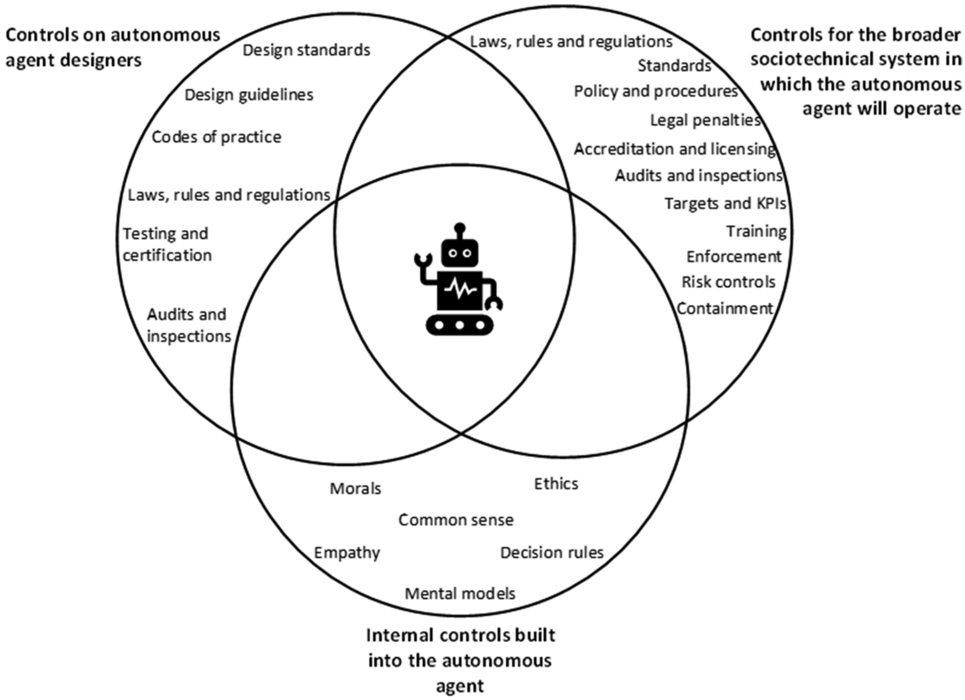

Figure 3. Examples of the controls required to manage the risks associated with artificial general intelligence (AGI).

programs underpinned by a system's thinking approach considering micro, macro and meso levels (Grote, Weyer, and Stanton 2014; Leveson 2004; Rasmussen 1997; Salmon et al. 2021).

The result proved to be an AGI that optimized human health and wellbeing through the design of safe, healthy, and meaningful human work. Rather than excise human work entirely, SOTERIA jointly optimized the human and technical elements of work, whilst facilitating removal of injury risks and advancing rewarding work. AI robots were introduced, but frequently their role was to assist human workers rather than replace them. SOTERIA explained to its owners and controllers that zero harm was unattainable, and therefore target goals were revised. Workplace injuries and fatalities were not extirpated entirely, but SOTERIA had developed systems thinking-based incident reporting and learning systems which enabled rapid learning about the conditions that were creating injury (Goode et al. 2018; Salmon et al. 2017b). These revealed powerful contributory factors at the higher levels of work systems and associated with CEOs, regulatory bodies, and governments.

It should be noted that SOTERIA used participatory co-design processes inclusive of human workers, consistent with, and underpinned by, STS theory to develop safety interventions. Systems thinking methods such as PreventiMap (Goode et al. 2016) were used to assist this process and target relevant leverage points. The result was highly effective interventions which sought not to fix broken components, but instead to achieve broader work system reform (Dekker 2011). As workplace safety improved and injuries decreased, the cost savings and efficiencies enabled a reduction of working hours and the introduction of a four-day working week. Humanity flourished, engaged in safe and meaningful work but with more proportionate time for leisure pursuits. A system's thinking approach enabled the design of a safe and ethical AGI that posed no risk to the future of humanity.

2.4. Importance to HFE discipline and profession

The *Evolution in Societal Thinking* challenge is important for many reasons, two of which are discussed here. First, as HFE is the discipline concerned with enhancing human health and wellbeing, a failure to manage global risks can conceivably be considered a failure of HFE to fulfil its mission statement. As the application of systems HFE is required to successfully manage global risks, the proposed shift in thinking is critical to ensure that HFE is able to achieve its mission of enhancing human health and wellbeing. A beneficial impact of the proposed shift is the upskilling of HFE researchers and practitioners in systems thinking models and methods, which in turn will enhance the utility of HFE in all problem spaces. Second, we see responding to this challenge as an opportunity for HFE to demonstrate leadership by showcasing how systems HFE can practically be used for real world benefit. This in turn will enhance awareness and uptake of HFE, both in practice and across other disciples. Increasing the awareness of HFE has been identified as critical for the discipline moving forward, particularly in areas where HFE is not readily applied (Salmon et al. 2023).

2.5. HF/E strategy to address this challenge

Changing paradigms is no easy task (Meadows 2008), however, HFE researchers and practitioners can help facilitate our desired evolution in societal thinking. Further work applying systems HFE to understand and respond to global risks is encouraged (Salmon et al. 2021; Thatcher, Laughton, et al. 2018, Thatcher, Nayak, and Waterson 2020). This will be useful to showcase the benefits of a systems thinking approach. It is unfortunate that HFE has yet to effectively communicate its utility to the disciplines involved in tackling global risks (Salmon et al. 2019b; Thatcher, Laughton, et al. 2018, Thatcher, Nayak, and Waterson 2020). As pointed out by Meadows (2008), such issues remain 'despite the analytical and technical brilliance that has been directed toward eradicating them'. There is also a need to gather formal evidence on the impacts of systems HFE and to communicate success stories in which systems HFE has been applied with positive outcomes. These narratives exist, but those interested in systems thinking must go and find them. They are not as readily discussed as they should be.

Education and training in systems thinking and systems HFE is another area where immediate gains can be made. From our early stages of maturation, we intuitively think in systems. However, reductionist mental models are often instilled at an early age. As well as improving education and training programs for HFE researchers and practitioners (Salmon et al. 2023), it is our view that systems thinking should be taught in schools and become a basic module of all university degrees. As it does not reside in any discrete discipline, systems thinking should also be taught across all disciplines. Finally, practical guidance on the methods used to enact the systems thinking philosophy is critical. Although there are some examples of guidance in applying systems thinking methods (e.g. Sterman 2000; Stanton 2004), there is certainly space for many (Salmon et al. 2022b).

2.6. Ramifications for HFE in developing countries

Responding to this challenge has many potential benefits for developing countries, both generally and specifically for the HFE discipline. Developing countries face many global risks, including issues such as poverty, food security, limited access to healthcare and education, corruption, and gender inequalities. A shift toward systems thinking will enable a better understanding of such issues and critically will support the development of low cost and effective solutions *via* the identification of powerful leverage points. For HFE specifically, the shift to systems thinking will support the upskilling of HFE researchers and practitioners in systems HFE models and methods, which in turn will enable more systems thinking-based applications. The shift will therefore support developing countries in responding to complex issues and will enhance HFE researcher and practitioner skill-sets.

2.7. Future prospects

Society is manifestly failing to successfully manage a growing set of complex global risks (Hancock 2019; Salmon and Plant 2022a). Effectively responding to such risks requires a shift towards systems thinking, not only in HFE, but across society generally. We encourage HFE researchers and practitioners to enact this change through further applications of systems HFE to help understand and respond to complex global risks.

3. Grand HFE challenge: future of work in Industry 5.0

3.1. Introduction to the future of human work in Industry 5.0

This section provides an overview of the grand HFE challenge associated with the future of human work in the context of Industry 5.0. Industry 4.0 focuses on smart factories, widespread digitization, and cyber-physical convergence enabled by disruptive trends in automation, robotization, big data analytics, smart systems, virtualization, AI, machine learning and Internet of Things. Industry 5.0 moves beyond the enterprise and directs focus to the human-system dyad; it assumes that the potential for advancement relies on perfecting collaboration among humans and machines.

Industry 4.0, is coupling massive data, advances in artificial intelligence and machine learning, emerging technologies, and unprecedented levels of autonomy to revolutionize the future of human work. It will usher in a digital reality that promises to reach beyond the enterprise, fundamentally altering not only the way people work, but also how they live and play. At the core of *Industry 4.0* is real-time, data analytic-driven intelligence. As Gartner (Cotteleer and Sniderman 2017) states:

> *The integration of digital information from many different sources and locations [throughout the enterprise] can drive the physical act of doing business, in an ongoing cycle. Throughout this cycle, real-time access to data and intelligence is driven by the continuous and cyclical flow of information and actions between the physical and digital worlds. This flow occurs through an iterative series of three steps collectively known as the physical-to-digital-to-physical (PDP) loop. To achieve this process, Industry 4.0 combines relevant physical and digital technologies, including analytics, additive manufacturing, robotics, high-performance computing, natural language processing, artificial intelligence and cognitive technologies, advanced materials, and augmented reality.*

This PDP loop representation of Industry 4.0, which has been widely adopted, leaves out a fundamental component… the human. That is where Industry 5.0 comes in. The continuous and cyclical flow of information and actions will not only be between the physical and digital worlds but also incorporate the human as well. Thus, there will be a physical/ human-to-digital-to-physical (P/H-DP) loop (see Figure 4). By opening up the aperture to include a view of the human, HFE challenges of data transparency, emerging technology accessibility, trust in automation, and misinformation arise within Industry 4.0. These challenges are to be addressed through the concept of Industry 5.0, which *provides a vision of industry that aims beyond efficiency and productivity as the sole goals, and reinforces the role and the contribution of industry to society* (European Commission 2022).

The Industry 5.0 revolution will couple advanced manufacturing and operational techniques with smart sensor and display technologies embedded within processes, assets, and people themselves, to realize a hyper-connected enterprise (Lu et al. 2022).

Beyond supporting interconnection and autonomy, this smart enterprise will use real-time data as a strategic asset to drive optimization, both of current and future operations. For example, digital twins which are *artificial intelligent virtual replicas of physical systems* (Barricelli, Casiraghi, and Fogli 2019; Semeraro et al. 2021; Van Der Horn and Mahadevan 2021) can be used to keep track of equipment maintenance and reduce costs associated with preventable equipment failure, while eXtended Reality (XR) display technologies will be used to visualize pertinent information at the point-of-need to support consulting technical documents and optimizing productive capabilities. It will be of critical importance to ensure such display technologies are suitable to widespread adoption and do not come with inherent accessibility limitations.

Further, Industry 5.0 has the potential to support the people within these interconnected systems by developing a digital twin of the human (i.e. a digital phenotype). Once interconnected, it will be of critical importance to enhance transparency in autonomy, so people

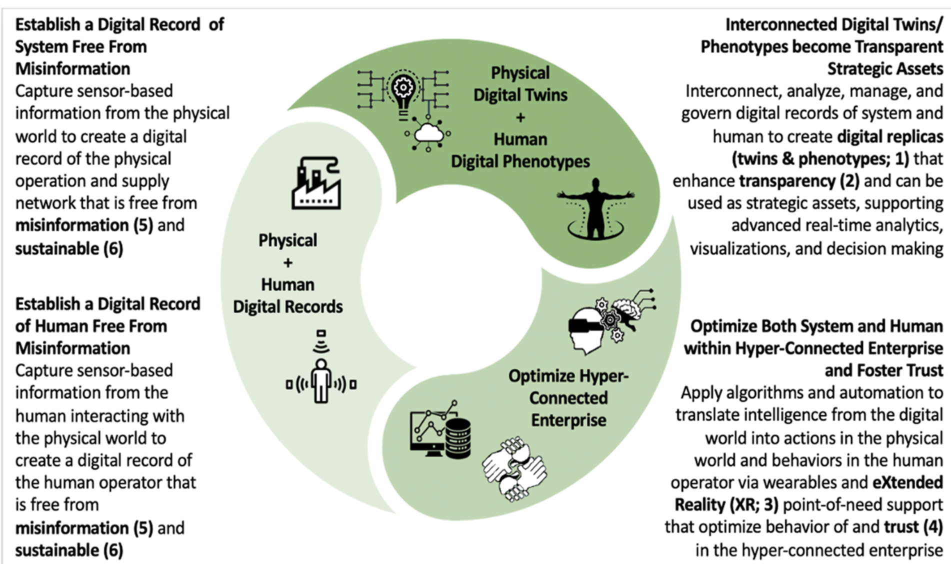

Figure 4. Industry 5.0's physical/human-to-digital-to-physical (P/H-DP) Loop (adapted from Cotteleer and Sniderman 2017) (note: Numbers refer to below grand challenge areas).

understand the systems they are connected to, as well as enhance their trust in those systems. Real-time sensor data (e.g. HRV, EDA, EGG) can be gathered during the workday to monitor trust in the systems connected to humans. In addition, as part of monitoring the state of the human, these sensor data can be used to develop digital phenotypes that monitor physical (to trigger stretching exercises) and cognitive stress (to trigger mindfulness exercises), frustration (to trigger point-of-need training), and engagement (to trigger retention strategies). As workers engage with intelligent systems, such digital phenotypes can be used to elevate human capabilities and well-being in a manner that is adaptive, innovative, and engaging, thereby making the future of work more valuable and meaningful. With all the data available for optimization of both systems and humans within Industry 5.0, it will be of critical importance to ensure high digital and data literacies to minimize any associated ill effects of misinformation, while maximizing the benefits to the workforce. Thus, across the globe, Industry 5.0 aims to transform how systems, parts, and products are designed, produced, used, and maintained while extending beyond the factory floor to transform how organizations and people make sense of information and act upon it to optimize human-system integration. Importantly, it also provides the opportunity to enhance the skill sets, health, and welfare of the workforce and the suppliers, customers, and recipients of their products/services.

3.1.1. Ramifications of Industry 5.0 for HFE

Industry 5.0, while often associated with manufacturing, is not limited to it. The concept represents an industrial revolution, marked by an unprecedented integration of advanced technologies and a renewed focus on the human element in the workplace across various sectors beyond manufacturing, such as healthcare, agriculture, retail, and more. With Industry 5.0, the rapid advancements in AI, robotics, smart sensors and controls, and digital connectivity are not merely reshaping the tools we use but are also redefining the very nature of work itself (Briken et al. 2023; Enang, Bashiri, and Jarvis 2023). Furthermore, the transformation in human work is happening in both developed and developing countries. For example, in countries like Germany and the United States, there are numerous examples of smart factories where automation, IoT (Internet of Things), and AI are integrated into manufacturing processes. Siemens' Amberg Electronics Plant in Germany is a leading example, showcasing highly automated production processes and digital monitoring systems (Rajiv and Johnson 2017). In addition, collaborative robots (co-bots) are increasingly used in the workplace. These co-bots work alongside humans, assisting in tasks that are either too dangerous, repetitive, or require precision. One example is the use of intelligent construction robots, such as the semi-automated robot (SAM) 100, to work alongside construction workers, which leads to enhanced productivity and reduced physical strain associated with the repetitive task of bricklaying (Tyrangiel 2020). In countries like India and Kenya, mobile technology and IoT are being used to transform agriculture. Farmers use AI-enabled mobile apps for weather forecasts (Agyekum, Antwi-Agyei, and Dougill 2022) and crop health monitoring and diagnosis (Mehetre et al. 2023), helping them make better decisions. In Vietnam's textile and garment industry, 'applying advanced science and technology based on information technology and artificial intelligence' is identified as one of their key development strategies (Vietnam Apparel and Textile Association, 2022).

3.1.2. Importance to HFE discipline and profession

Six key HFE challenge areas that should be addressed in the near future to realize the human-centered manufacturing concepts of Industry 5.0 include but are not limited to (1) determining how best to support human digital twin integration with cyber-physical systems, (2) ensuring transparency of and fostering trust in related data, (3) analytics and autonomy, (4) ensuring accessibility of emerging technologies, such as XR displays, (5) combatting the ill effects of misinformation, and (6) sustainability and resilience. These challenge areas are discussed below.

3.2. Challenge area #1: human digital twin integration with cyber-physical systems

A concept of a human digital twin (HDT), was proposed as a centralized digital representation of relevant human data for integration into the cyber-physical systems (CPS) in the quest to address the challenges in human-centered manufacturing and leading to the definition of the human-cyber-physical systems (HCPS) (Sparrow, Kruger, and Basson 2019; Wang et al. 2024). As such, HDT points to the importance of humans in integrating the physical world and virtual world (Wang et al. 2022). According to Cotta, Lopes, and Vassallo (2023), HDT includes physical representations and virtual models of humans to accurately track and represent human motion, perception, and manipulation capabilities. It should be noted that the concept of HDT should not be confused with the concept of the digital twin (DT) itself (Tao et al. 2019), which refers to the 'virtual representation of a single instance of a physical system along with the data/information from the physical system that is used to update the states of the virtual representation over time (Van Der Horn and Mahadevan 2021).

Industry 5.0 aims to develop a synergistic coupling between physical systems, mass sensor data, smart digital technologies, and human operators to provide real-time optimization of processes, systems, and people (Yang et al. 2019). To achieve this synergy, there is a need to carefully consider how best to adopt a human-centric strategy that realizes effective HDT-cyber-physical production systems integration. Much work is being focused on the CPS-digital twin side of the loop (i.e. establishing a digital replica of the system, including its constituent technologies: Internet of Things (IOT), Cloud Computing (CC), Big Data Analytics (BDA), and machine learning (ML)/artificial intelligence (AI). The human-digital twin side of this loop (i.e. establishing a digital replica of the human) does not receive as much consideration in the discourse and research surrounding Industry 4.0. Yet, the human becomes a critical focus in Industry 5.0, as we navigate profound changes in the role of the human as a component of a highly interconnected enterprise (Neumann et al. 2021). From the HDT (Sparrow, Kruger, and Basson 2019) side of this coupling, often the term 'digital phenotype' (Jagesar, Vorstman, and Kas 2021) is used to describe models that leverage data streams from personal devices, such as smartphones and wearables, to model a person's real-time psychomotor behavior and cognitive/affective states. If carefully designed, such HDTs can be used to capture and model past, present, and predicted human behavior, thereby optimizing human performance, physiological state, and psychological state, while improving progress monitoring, reducing the potential for injuries, increasing workforce well-being, and enhancing safety in Industry 5.0's interconnected cyber-physical systems.

3.2.1. Importance to HFE discipline and profession

Critical questions need to be answered in order to design digital phenotypes that effectively realize the HDT-CPS integration, including but not limited to:

- What is the role of the human and what does a human-centric strategy look like in Industry 5.0?
- What is the optimal design for human-digital twin-physical systems integration?
- Is moment-to-moment human performance meant to be optimized?
- Once human performance can be optimized, will this lead to an imbalance in the welfare of organizations versus their workforce?
- Will Industry 5.0 give rise to unethical hiring/firing practices?
- Will focus on human performance optimization compromise human physiology or psychology, potentially reducing lifespan?
- Will focus on epiphenomena, for instance present suboptimal human performance compared to past performance, rather than on biological or psychological etiology cause harm to the human?
- Which sensors are most effective at capturing the real-time state of the human as a component of a highly interconnected enterprise?
- Once sensor data on human state are collected, who owns these data and are there privacy concerns?
- Which physical human behaviors should be captured (e.g. gesture tracking, eye tracking, speech capture, etc.)?
- Which cognitive states should be modeled (e.g. overload, distraction, etc.)?
- Which affective states should be modeled (e.g. arousal, engagement, stress, etc.)?

3.3. Challenge area #2: enabling human-centered transparent artificial intelligence/autonomy

Autonomous and robotic systems are increasingly used in various domains (Harel, Marron, and Sifakis 2020). Take the healthcare domain for example, AI-based clinical decision support systems (CDSS) have been developed, aimed at enhancing patient safety in clinical practice. In one instance, a deep-learning system for diagnosing cardiovascular diseases using cardiac MRI images was approved by the FDA in 2018 (Marr 2017). Another example is a decision aid based on convolutional neural networks (CNN), which achieved dermatologist-level accuracy in diagnosing skin malignancy (Esteva et al. 2017). In developing countries, we also observe an upward momentum for developing AI-based clinical decision aids. For example, Ubenwa, a start-up in Nigeria, uses machine learning to improve the diagnosis of birth asphyxia in low-resource settings (Onu et al. 2019).

There are challenges associated with such autonomy. Specifically, as autonomous and robotic systems become more intelligent, humans may have difficulty deciphering AI/autonomy-generated solutions and increasingly perceive them as a mysterious black box that is difficult to trust (Gentile, Donmez, and Jamieson 2023; Peters et al. 2024; Shin 2021; Zerilli, Bhatt, and Weller 2022). How to 'open the black box' becomes a research topic that attracts interest from multiple disciplines including explainable AI and HFE researchers. Explainable artificial intelligence (XAI) is concerned with developing new methods that explain and interpret machine learning models to allow human users to comprehend and trust the results and output created by machine learning algorithms (Hois, Theofanou-Fuelbier, and Junk 2019; IBM. 2022; Linardatos, Papastefanopoulos, and Kotsiantis 2020; Sanneman and Shah 2022). Despite the different terms, the common goal is to enable the communication of decision-making rationales to the human such that they can better comprehend and interpret AI/autonomy-generated solutions. This research is thus needed to ensure the data sources within Industry 5.0's D/H-DT loop become transparent strategic assets. From the algorithmic perspective, some algorithms such as regression models and decision trees are inherently more explainable, while others such as deep neural networks are inherently 'opaque'. AI researchers focus primarily on the latter type, and various types of post-hoc explanation techniques have been developed (Guidotti et al. 2019).

Rather than focusing on developing algorithmic methods, HFE researchers focus on identifying the type and structure of information that needs to be conveyed to the human agents to enhance autonomy transparency (. There are multiple definitions of autonomy transparency: 'the [degree of] shared intent and shared awareness between a human and a machine (Lyons and Havig 2014)', 'the extent to which an autonomous agent can convey its intent, performance, future plans and reasoning process' (Chen, Conroy, and Rubin 2015), and 'the understandability and predictability of their actions' (Endsley 2017). Despite the lack of a universal definition, we observe a fairly consistent pattern: a transparent autonomy should communicate to the human agent the autonomy's ability, its decision-making rationale, and its intent and future plans (Luo, Du, and Yang 2022). Research has shown that conveying the autonomous system's reliability, confidence, and reason for actions and errors (even in handcrafted forms) can facilitate appropriate trust and dependence behaviors and can improve human-autonomy team performance (Dzindolet et al. 2003; McGuirl and Sarter 2006; Wang, Jamieson, and Hollands 2009; Yang et al. 2017). The situation awareness-based agent transparency (SAT) model is also proposed to convey information supporting the human agent's perception, comprehension, and projection of an intelligent assistant's recommendations (Chen et al. 2018; Mercado et al. 2016). Such transparency will become ever more important in the massive data environment of Industry 5.0.

3.3.1. Importance to HFE discipline and profession

Despite existing research efforts, there are several key challenges for enabling human-centered explainable AI/autonomy, including but not limited to the following issues:

- How can the need for explainability or transparency be identified for different user groups? For example, an airport security screening officer may value the confidence interval of the computer vision algorithm highly, while a medical doctor may be interested to find out if s/he changes the patient's medication, how will the projected prognosis change.
- As described in the work of Miller (2019), research in psychology and cognitive science has investigated how people define, generate, and present explanations (to another person). How can such existing research be leveraged in designing transparent autonomy?
- How does explainability or transparency interact with other human factors constructs, for example, workload? As perceiving and making sense of information is often

cognitively demanding, how does one make tradeoff decisions between explainability or transparency and other constructs? This is especially valid in the context of self-driving cars, where explainability may influence mental models, trust, response, and system performance (Schraagen et al. 2020; Omeiza et al. 2022).

Industry 5.0 also promotes the development of transparency in the enterprise *via* massive data and analytics, transparency of the enterprise *via* massive data and analytics, providing a detailed view into the full supply chain, more real-time data regarding the health of assets and systems, more insight into the well-being of the workforce, and more. It will be essential to ensure such transparency, as without it the vision of a highly intelligent and hyper-connected enterprise cannot be realized.

3.4. Challenge area #3: extended reality technology accessibility

The eXtended Reality (XR) technologies, which offer a range of computer-generated immersive experiences that mirror reality to varying degrees, are an integral component of Industry 5.0 destined to revolutionize the manner in which we work, collaborate, and advance our careers (Tromp, Le, and Le 2020). For example, XR technology is anticipated to fill many enterprise roles in the coming decades, from training to maintenance to operational support to design, and more. Many Fortune 500 companies are testing and/or deploying XR solutions (Allied Market Research Report 2021). XR accessibility limitations can create a divide in Industry 5.0, with those who can tolerate XR exposure advancing due to better, more immersive training, more effective repair jobs aided by real-time augmented guidance, more creative designs that evolve from a mesh of digital and physical worlds, etc., while those who are susceptible to the ill effects of XR technology are left on the sidelines watching this new era of XR empowered productivity pass them by. Further, if XR is indeed sexist, with females unable to harness its bevy of performance enhancing potential in the same manner as males, this has the potential to drive a deeper economic divide between the sexes. It is already speculated that global economic equality between the sexes will take another ~135 years (World Economic Forum 2021) and XR accessibility limitations in Industry 5.0 could widen this gap.

XR technologies can be used in a wide range of settings, including manufacturing (Fast-Berglund, Gong, and Li 2018), training (Burian et al. 2023), rehabilitation (Schuermans et al. 2022), and so on. It also can be used to personalize operational support and training, providing the right information at the right time in the right context, which can lead to substantial gains in human performance (Stanney, Skinner, and Hughes 2023). Yet, exposure to XR systems often produces unwanted side effects that could render user's incapable of remaining immersed in the XR environment or functioning effectively upon return to the real world (Stanney, Lawson, et al. 2020). These adverse effects may include nausea and vomiting, postural instability, reduced dexterity, visual disturbances, and profound drowsiness. As users subsequently take on their normal routines, unaware of these lingering effects, their safety and well-being may be compromised. In general, those who have studied these ill effects associated with XR exposure oftentimes report that females are more susceptible than males. Yet when a large number of studies examining sex differences in motion sickness were reviewed (Lawson 2014), only about half found higher levels of susceptibility in females as compared to males. When these differences were examined further, the design of the technology itself, not attributes associated with females, was found to be the primary driver of sex differences (Stanney, Lawson, et al. 2020). When the design of the XR technology matched the anthropometrics of females, sex differences were no longer detectable. Thus, sex differences have been 'designed in' to XR systems, particularly because XR headsets have been designed around the average anthropometrics of males. This could lead to accessibility limitations for XR technology based on sex, anthropometrics, disabilities, digital literacy, which could have a profound effect on those who are susceptible.

3.4.1. Importance to HFE discipline and profession

Critical questions need to be answered in order to ensure XR technology is accessible to all, including but not limited to:

- What does universal design mean to XR technology?
- What type of practical resource (tools, platforms, etc.) for developers to access and share are needed to ensure XR accessibility?
- How can susceptibility differences be designed out of XR technology?
- Are there other such burgeoning and impactful Industry 5.0 technologies that have been designed around the average anthropometrics of males that may create additional accessibility divides?
- What sex, anthropometric, disability, digital literacy, and other XR susceptibility differences matter in Industry 5.0?
- Are there other critical anthropometric variables or limitations (e.g. sensory impairments, mobility issues) that need to be identified, which could drive accessibility limitations in Industry 5.0?
- How must standard accommodations for two-dimensional media be updated to address accessibility needs in three-dimensional spaces?
- Will a digital divide designed into XR technology drive a deeper economic divide between the sexes or others with susceptibility limitations?

It is essential to get out ahead of and tackle this dilemma, so that accessibility limitations are minimized such that all individuals can benefit from the burgeoning array of XR and other emerging technologies that are situated to accelerate human performance and learning in Industry 5.0.

3.5. Challenge area #4: enabling trustworthy autonomy

In the Industry 5.0 workspace, humans and autonomous systems (machines) are expected to work together as a team, collaborating intelligently to complete tasks. While the relevant human-centered design issues in advanced manufacturing systems have been widely published (Alves, Lima, and Gaspar 2023; Lu et al. 2022; Long and Magerko 2020; Nahavandi 2019), other industry sectors are also exposed to the problem of trustworthy autonomy. For example, consider a collaborative robot (co-bot), that works alongside a human seamlessly. The co-bot could assist surgeons in surgical operations with unparalleled precision and could work alongside human workers in manufacturing settings to handle tasks that require strength and endurance. In agriculture, the co-bot could assist farmers with tasks like harvesting and pest control. Even though the hypothetical scenario is not fully a reality yet, researchers are actively working on developing autonomous/robotic systems toward this goal. One example is the increasing use of robots in the construction industry. Arguably one of the most labor-intensive industries, the construction industry faces challenges of worker shortages and occupational health and safety issues (Zhang et al. 2023). As a potential solution, robots have been increasingly introduced into architecture and construction (AEC). The Semi-automated Robot (SAM) 100 (Tyrangiel 2020) can build walls six times faster than human workers; the Material Unit Lift Enhancer (MULE) is a lift-assist robot designed to transport construction material of up to 135 lb. (Spicer 2020). However, none of the robots can operate fully autonomously, and close collaboration with humans is absolutely necessary. The expected result of human-autonomy teaming is to optimize both the system and human within hyper-connected enterprise. To achieve this objective, it will be essential to foster trust between human and system (see Figure 5). Humans and autonomous systems possess complementary capabilities. For example, humans are good at solving poorly defined problems that require creativity and adaptivity and good at tasks that require social skills. Machines can analyze large amounts of data at a high speed impossible for humans and could outperform humans on well-defined questions. For the human-machine partnership to function optimally in Industry 5.0, it is essential to understand how the two agents (human and system) can effectively work together and trust one another.

To enable effective human-autonomy teaming, trust is considered a key factor. Trust in automation, or more recently, trust in autonomy, is defined as 'the attitude that an

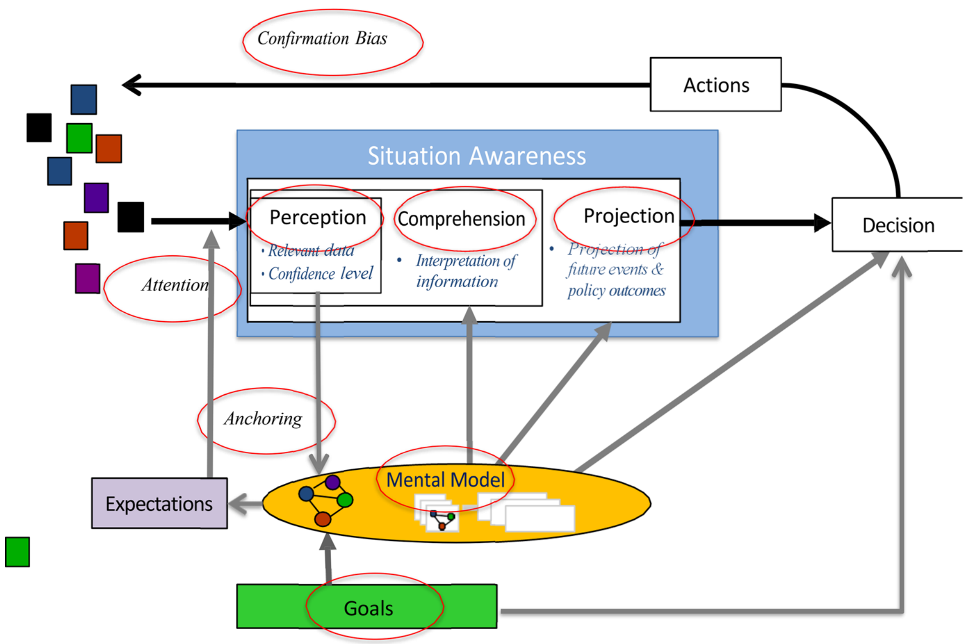

Figure 5. Information attacks can affect human *decision* making by redirecting their attention to emotionally charged headlines, anchoring on early but incorrect stories, reinforcing existing mental models to create confirmation bias, and undermining situation awareness by attacking confidence in valid information, information overload, and people's ability to interpret and project from existing data (adapted from Endsley 2018).

(autonomous) agent will help achieve an individual's goals in a situation characterized by uncertainty and vulnerability' (Lee and See 2004). Trust in autonomy has attracted substantial research attention in the past three decades. More than two dozen factors have been identified to influence one's (snapshot) trust in automation, including individual factors, system factors and environmental factors (for a comprehensive review of factors, refer to Hoff and Bashir 2015 and Schaefer et al. 2016). More recently, researchers started to investigate the temporal dynamics of trust, trying to understand how trust strengthens or decays due to moment-to-moment interactions with automation (de Visser et al. 2020; Guo and Yang 2021).

3.5.1. Importance to HFE discipline and profession

Despite existing research efforts, there are several key challenges for enabling trustworthy AI/autonomy in Industry 5.0, including but not limited to:

- What factors can influence a human agent's trust formation and evolution over time?
- How can the trust evolution process be modeled computationally?
- If we can model and predict the human agent's trust in the autonomous agent accurately, how can trust-aware autonomous decision making be enabled?
- Existing studies on trust in automation are focused on dyadic teams consisting of one human agent and one autonomous agent. How can the human agent's trust in multi-agent settings be modeled, wherein multiple human agents and multiple autonomous agents co-exist and interact?
- If the autonomous agent is to become a true teammate in Industry 5.0, the trust relationship will need to expand from a one-way to a two-way relationship, i.e. the human agent's trust in the autonomous agent and the autonomous agent's trust in the human. How can such a bi-directional trust relationship be modeled?

Industry 5.0 promises to transform the enterprise such that it is highly intelligent, hyper-connected, and optimized. However, to realize this vision, faith in data and trust in the AI that will aggregate, analyze and act on that data are essential.

3.6. Challenge area #5: combatting misinformation

It is essential that the data sources and digital replicas that aim to transform work in Industry 5.0 are free from misinformation. Misinformation, including fake news, rumors, disinformation, is misleading or incorrect information presented as fact, either intentionally or unintentionally. Misinformation rose rapidly since 2016 and even became 2018s word of the year (Strauss, 2018). 'Today, media outlets are known to report news in a biased way, potentially affecting the beliefs of news consumers and altering their behaviors… (in addition, as) social media has become a powerful means for expressing opinions, what is feared is how it is slowly programming users' behaviors' (Aggarwal et al. 2020). Specifically, media bias has been known to propagate fear (O'Connell 1999), alter political views (Gerber, Karlan, and Bergan 2009; Knight and Chiang 2008), shape public opinion (Huang, Cook, and Xie 2021), among other ill effects. Further, because of known human decision biases, such as anchoring, confirmation bias, and cognitive dissonance, misinformation is more likely to be accepted than legitimate information. Misinformation and fake news generate 83% more page views than validated information (Clarke et al. 2021). According to a report by MIT Sloan, falsehoods are 70% more likely to be shared than the truth (Vosoughi, Roy, and Aral 2018). Fostered by the recent advances in social media, the ability for inaccurate information to spread more rapidly and widely than accurate information has created a new challenge that undermines people's ability to think independently and make informed decisions.

As Industry 5.0 evolves, and a plethora of digital replicas of both system and human arise, should misinformation within the enterprise be of concern? Misinformation has already risen as a real issue at the workplace. A study done by Leadership IQ showed that 59% of the leaders and professionals surveyed were concerned about fake news in their workplace (Leadership IQ Report, 2017). Further, preventing the spread of misinformation at work is a top priority for executives-level managers (FirstUp 2022). Employees have been identified as the best ambassadors in an era of declining trust, especially because more than eight in ten Americans said they are concerned about the spread of false information (Newall 2020). Such concerns have merit, as independent thinking is known to foster outstanding scholarship (Chen 2008), creativity (Pawlak 2000), the ability to navigate the complexities of life (Murphy 2010), and more. While groupthink tends to prioritize harmony and conformity, associated biases impair rational cost-benefit analyses of available trade-offs (Joffe 2021). Such a loss of independent thinking could result in dysfunctional decision-making and fixation on suboptimal courses of action that do not deliberately consider of all relevant information. As Industry 5.0 is all about the intelligence that can be derived from data and analytics, misinformation and associated biased behavior could hinder the efficacy of data-driven decision-making, thereby limiting expected gains in productivity and professional and personal growth. It will be important to increase digital and data literacies to minimize such ill effects (Carmi et al. 2020).

Misinformation could be picked up at work through formal or informal conversations, or outside of work through social media or news sources. As the line between our personal and professional lives remains blurry, organizations, small and large, start to realize the impact of misinformation on work. Conspiracy theories and all manner of bad information are corrupting the quality of information in our world, and it has already begun to affect businesses. For example, McKinsey's report showed ongoing circulation of wild and unproven rumors around COVID-19 have impacted how organizations defined policies during the pandemic and have led to economic and human resources loss (McKinsey Executive Briefing, 2022). Another report published by Forbes pointed out the success of return to office policy depends on whether people believe in the science behind the recommendations because there are so many false sources of information in circulation regarding COVID-19 (Kohler 2020).

3.6.1. Importance to HFE discipline and profession

The HFE profession can play a significant role in addressing this challenge by addressing several key challenges associated with creating improved methods for information presentation and for supporting the assessment of information confidence, including but not limited to:

- Which biases have the most impact on believing misinformation?
- How to model the emotional aspects of misinformation and find ways for reducing defensive mindsets and for increasing objective information processing over directed reasoning?

- How to develop methodologies to measure the impact of misinformation on an organization or business?
- How to build processes and take programmatic approaches to stop the spread of misinformation at wwork?
- How to create educational materials to empower employees or members of an organization with the knowledge and the cognitive tools to make sense of the information driving an organization's decision-making?

It is critical that research be devoted to these and other related questions to effectively design Industry 5.0 technology solutions that can foster independent thinking and avoid biases associated with misinformation.

3.7. Challenge area 6: sustainability and resilience

Industry 4.0 seeks for organizations to become more automated and data-driven to drive higher levels of agility and flexibility. Industry 5.0 broadens the aperture to address resilience as well, such that it is possible to derive lessons-learned from ongoing operations, use this knowledge to predict future trends and put corrective action plans in place that ensure stable and sustainable performance (Adel 2022).

Traditionally, such sustainability efforts focus on reducing or minimizing damage and/or waste. Under Industry 5.0, the focus goes beyond reducing a company's negative impact (e.g. environmental), and places attention on increasing their positive impact and making the world a better place (e.g. enhance society). For example, careful design of the collaboration among humans and systems can lead to reduced waste and overproduction, uncover ways to repurpose, recycle and recover assets, and boost personalization of training to provide workers with sustainable skills.

3.7.1. Importance to HFE discipline and profession

There are several key issues for enabling sustainability and resilience in Industry 5.0, including but not limited to:

- What emerging technologies are needed to achieve sustainability and resilience goals?
- How must production processes be rethought to enable re-use, repurposing, and recycling of natural resources, thereby reducing waste, minimizing environmental damage and respecting the production limits of the planet?
- How can AI and data analytics be used to optimize energy consumption, reduce waste, optimize delivery schedules, and minimize environmental impacts?
- How can flexible, reconfigurable and agile systems be achieved that increase robustness and make them more resistant to operational changes and disruptions, such as pandemics, geopolitical events, and natural disasters, thereby sustaining required operations under normal and abnormal conditions?
- How can social value creation be maximized in Industry 5.0?
- How can human-centric strategy to Industry 5.0 ultimately address human needs as defined in Maslow's hierarchy of needs, such that not only basic physiological and

safety needs are met, but also human capabilities are enhanced and self-actualization is supported?
- How can Industry 5.0 ensure a transformative impact on society, such as by ensuring workers skills are resilient even in the face of changing roles and responsibilities?

Taken together, these sustainability measures should lead to a higher level of resilience against disturbances and disasters, such as COVID-19.

3.8. Future prospects

Although Industry 5.0's modern technologies, including digital twins, digital phenotypes, XR, AI/autonomy, and more, have promised to fundamentally alter the way people work, live, and play, the result may be greatly diminished by a lack of data and analytic transparency, accessibility limitations, a plethora of mistrust, an abundance of misinformation and disinformation, and a lack of sustainability and resilience.

Effectively dealing with the challenge areas discussed above will require an understanding of the interactions between the human, system, social, and technical components within Industry 5.0, and the concentrated efforts of the human factors profession. By effectively addressing these challenge areas, the future of human work in Industry 5.0 is anticipated to be highly transformational for both the systems within the enterprise, as well as the humans interacting with those systems, and even reaching beyond the enterprise to benefit society as a whole. In terms of the latter, by taking careful consideration of the human in the P/H-DP loop, future work can be redefined in a manner that not only increases enterprise efficiencies, but also has the potential to make the workplace inherently more valuable and meaningful to the workforce.

4. Grand HFE challenge: climate change and sustainability

4.1. Introduction to the climate change and sustainability

In recent decades it has become apparent that individual and collective human activity has grown to such an extent that it has disrupted a number of important Earth-system cycles. The most well-known of these is the disruption to the carbon cycle leading to the accumulation of carbon dioxide and methane in the atmosphere and the greenhouse effect, otherwise known as climate change (Cook et al. 2016).

Anthropogenic climate change has already led to temperature extremes (Foster, Royer, and Lunt 2017), sea-level rises (Kulp and Strauss 2019), fresh-water scarcity (Farinosi et al. 2018), and mass migration (Hoffmann et al. 2020) and these are likely to become more frequent in the coming decades (IPCC 2021). The consequences of individual and collective human actions on our life-sustaining environment extend beyond climate change to include nitrogen cycle disruptions (Sinha, Michalak, and Balaji 2017), mass extinctions (Ceballos, Ehrlich, and Dirzo 2017), air pollution (Landrigan et al. 2018), and plastic accumulation in our oceans (Lebreton et al. 2018). Unless addressed, the issues raised by sustainability pose an existential crisis for humanity and the potential collapse of our existing economic, social, and environmental systems this century (Hancock 2019; Herrington 2021). Since

HFE is concerned with human health, wellbeing and performance, and these issues are unmistakably caused by human actions, sustainability and climate change issues therefore clearly qualify as a grand challenge for HFE. von Carlowitz (1732) was the first to use the term 'sustainability'. He recommended a sustainability framework for forestry to provide a continuous supply of wood for future human requirements including building materials, fuel for heating and cooking, physical supports for mining operations, and raw materials for the manufacturing of products. Sustainability has grown in importance with the realization that many of the resources we need to survive are finite and must be carefully managed for the good of all. More recently, Johnston et al. (2007) noted that there were multiple definitions of sustainability, with many of the definitions being loose or contradictory. In trying to consolidate these definitions Johnston et al. (2007) recommended four components of sustainability: (1) reducing the extraction of raw materials; (2) reducing materials produced and used by society; (3) preventing the degradation of nature; and (4) removing barriers that prevent people from meeting their current and future needs. While sustainability has often become synonymous with the need to preserve the natural environment, Johnston et al. (2007) definition makes it clear that it is essentially about the interplay between humans and the environment which provides all the resources for human survival. From an HFE perspective it is important to note that the core issue for sustainability is people and their survival in collaboration with the biosphere.

Sustainable development refers specifically to Johnston et al. (2007) fourth component and is encapsulated in the *World Commission on Environment and Development's* (1987) definition as: 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. Sustainable development is often equated with sustained growth, but too much (human) development inevitably means environmental degradation (Redclift 2005) and some people have even called for de-growth (Vazquez-Brust and Plaza-Úbeda 2021). While these concepts fall beyond the primary scope of HFE, they are important considerations, framing how HFE might contribute. In particular, HFE must consider how to facilitate development for all while taking resource constraints into account.

Sustainability and climate change can be considered a Grand Challenge for HFE because this requires fundamental change within the field, which is intimately linked to facilitating individual and collective human behavior change (see Table 3).

Table 3. Main challenge areas for E/HF and sustainability and climate change.

Main issues	Challenge areas
Design for mitigation	• Accurately communicating current resource use • Design of products, services, jobs, organizations, and public systems • Understanding and designing for behavior change
Design for adaptation	• Communicating risk, uncertainty, and resilience opportunities • Design of adaptable and resilient products, services, jobs, organizations, and public systems • Design of disaster management and planning
Complex systems thinking	• Scaling up from local to global • E/HF complex systems thinking tools • Context awareness and diversity
Educational challenges	• Core skills of participation, complex systems thinking, and adaptation to change • Core knowledge domains including the science of sustainability and climate change and existing E/HF approaches • Ethics and values in E/HF • Resilience, diversity, and context awareness education

4.2. Design for mitigation

Mitigation means reducing the impact of human behavior on resources (particularly energy, water, clean air, food, and human resources) and the reduction in the accumulation of waste (e.g. carbon dioxide, plastic, nitrogen, and heavy metals) that we and other species need for our sustained survival. This means making sociotechnical systems more resource efficient and effective from a whole-systems (including biospheric) perspective (Thatcher 2013). For HFE this means that we must contribute to the design of systems that change individual and collective human behavior to use resources more efficiently and effectively.

4.2.1. Communicating resource use for mitigation opportunities

Behavior change can be achieved simply through better communication of current resource use.

Communicating information clearly and unambiguously is a task that HFE has performed since its inception, especially through the design of interfaces. HFE has a long history understanding the physical and cognitive constraints of interface design to improve decision-making in simple and complex systems. This know-how needs to be translated to optimize climate change and sustainability communication. There are already a number of examples of HFE applied to the design of interfaces that are intended to assist with more effective or efficient resource use, although these are focused on energy consumption (e.g. Fang and Sun 2016; Hilliard and Jamieson 2008; Revell and Stanton 2016). Contributions to communicating energy consumption to become more efficient energy users is obviously vitally important, but there are also many opportunities to expand this work to include multiple other consumption (e.g. water usage, land use, deforestation, biodiversity, etc.) and waste production streams (e.g. heavy metals, sulphites, nitrous oxides, plastics, etc.). There are opportunities to design interfaces that communicate progress towards various sustainability goals that will motivate people to continue appropriate behaviors (e.g. recycling behavior, vegan/vegetarian diets, sanitation provision, employment opportunities, etc.). However, some of the feedback interfaces that are needed will require radical new thinking from the HFE community. Assets and resources are not equally distributed around the World and yet global supply chains enable these resources to be rapidly transported creating inequalities in access and production. For example, a monitor reporting the destruction of tropical forests will affect Brazil and Germany in different ways. Due to this interconnectedness, the destruction of tropical rainforests could mean the opportunity for an income for some, the ability to buy cheap fast food for others, or the collapse of vital ecosystems and biodiversity for others. HFE will need to arrive at new ways of representing this diversity of views.

4.2.2. Design of products, services, jobs, organizations, and public systems to be more resource effective/efficient

For HFE the challenge is less about the physical design of the systems themselves and more about how the systems encourage resource effective/efficient individual and collective behavior. HFE already has recommendations to achieve this goal: (1) preventing these behaviors from being carried out in the first place; (2) making it easier to perform these behaviors than resource inefficient/ineffective behaviors; or (3) minimizing the effect of these behaviors on resource consumption and/or waste production. HFE input for resource mitigation is needed in most areas where systems are being designed. The most obvious entry level for HFE is with products and services which the public associates most closely with HFE. Work has already started in this regard and includes the design of appliances for energy efficiency (e.g. Sauer, Wiese, and Rüttinger 2004; Sauer and Rüttinger 2004), the design of recycling centres (e.g. Durugbo 2013; Engkvist 2010), and the design of biophilic products (e.g. Claumann et al. 2009). Hanson (2013) and Hanson and Thatcher (2020) have provided numerous examples and suggestions for the role of HFE in the design of green jobs including for the energy, farming, transport, manufacturing, and services industries. Of course, it is not just green jobs that need to become more resource efficient/effective. Every job, indeed every task, requires careful consideration in terms of the resources consumed. It is likely that this will be a continual commitment as tasks/jobs evolve, the resources required change, and the technological systems advance. From the perspective of collective behavior and communities, it has also been shown that HFE can contribute to the resource efficiency/effectiveness design of much larger systems at the organizational level (e.g. Genaidy et al. (2009) work on lean manufacturing) and at the level of public systems (e.g. Hilliard and Jamieson (2011) work on electricity power grids).

4.2.3. Understanding and designing for behavior change

One of the biggest challenges for HFE will be understanding the resistance to individual and collective behavior change necessary to build a more sustainable world. Changing a person's behavior is a non-trivial task and this is not made easier by the significant impact of science and climate change denialism. At one level, it is easy to understand why science and climate change denialism is rife. Climate change and sustainability require humanity to radically rethink and redesign its political and economic systems in order to create a more equitable relationship for all within a bounded planetary system with finite resources. The necessary transitions must be achieved while the science is evolving, the time frames are relatively long (decades as opposed to seconds), and the outcomes are far from certain. However, it is important to note that the consequences of ignoring climate change and sustainability are catastrophic and potentially existential. In this context, denialism and misinformation is an unsurprising reaction. Nevertheless, to tackle this challenge will require the input of many disciplines, including HFE.

There has been some nascent work examining issues of behavior change for sustainability and climate change. For example, Ryan (2013) examined the human factors required for a shift towards adopting more sustainable public transport systems. The opportunities for HFE are endless. These might include: (1) understanding the HFE issues necessary for greater recycling behaviors; (2) the adoption of cycling and pedestrian routes; (3) the adoption of electric vehicles; (4) inclusion in renewable energy programs; (5) the adoption of meat-free or synthetic-meat diets; (6) farmers transitioning to organic farming methods (Coquil, Dedieu, and Béguin 2017); (7) how we reduce work-travel requirements; or (8) how we design communities and cities (Guimarães 2012) to meet all these required behavior changes. In addition, we will need to explore what sustainability and climate change means for the choices that we make in our own HFE discipline. Several authors have raised the issue of ethics and values required for the HFE field. Lange-Morales, Thatcher, and García-Acosta (2014) have proposed a set of underpinning values for the HFE discipline that will help us align our goals for a more sustainable future. These values are respect for the Earth, respect for human rights, appreciation of complexity, respect for diversity, respect for transparency and openness, and respect for ethical decision-making. We agree that these are important and recommend that these values be adopted.

4.3. Design for adaptation

Some scientists have suggested that a number of critical tipping points in the biosphere have already been reached (or will do so in the near future) and that mitigation measures will be insufficient to prevent the worst effects of our current unsustainable behaviors (Lenton et al. 2019). Instead, we will need to look at how we can adapt individual and collective behaviors and systems to cope with the negative effects of climate change and other disruptions to critical life-supporting climate services. This includes using HFE to show how we can adapt behaviors and systems to cope with extreme temperatures, extreme weather events, wildfires, changes in disease spreading, and sea level rises. But this also includes using HFE to show how we can adapt behaviors and systems to cope with disruptions to food supply chains (on land and in the oceans), water supplies and sanitation, healthcare service provision, mass migration, and job provision. The COVID-19 pandemic has shown as that we are still some way off being able to adequately adapt to these challenges in a timely manner.

4.3.1. Communicating risk, uncertainty, and resilience opportunities for long-term adaptation

One of the complicating factors with issues like climate change and sustainability is the information that needs to be communicated is often complex and ambiguous. For example, our understanding of climate change has evolved over decades and will continue to evolve over the next few decades. Impacts and consequences in the area of sustainability and climate change are not easy to predict, are non-uniform, and the exact timing is uncertain. Within the climate change arena, some geographical areas are predicted to get markedly warmer while other areas might get cooler. Predicted sea level rises will differentially affect parts of the planet and many high-lying inland areas will not be directly affected at all. For HFE this creates a challenge of how to effectively communicate the uncertainty and therefore the risk. Once again, communicating risk has been an HFE issue for many years (Brust-Renck, Royer, and Reyna 2013; Fischhoff 1995; Lipkus and Hollands 1999). Therefore, HFE already has a wealth of historical expertise that could help individuals, communities, and governments understand (and therefore prepare for) the risk and uncertainty of climate change. Most of the work on communicating the risks and uncertainty of issues such as climate change comes from outside HFE (Harold et al. 2016). Thatcher, Laughton et al. (2018) have made a nascent foray into this area, but there is much work still needed from the HFE community. This work is now urgent as advanced preparation allows more time to implement adaptation strategies.

4.3.2. Designing resilient products, services, jobs, organizations, and public systems

Designing for resilient complex systems is also an area where HFE has made significant contributions (e.g. Woods 2015). The principles of resilient, adaptable systems are fairly well understood in HFE although the areas of application require expansion. Sustainable, resilient, adaptable systems or those that retain their synergistic relationships with related systems (including natural systems) under conditions of instability. Hanson (2013) and Hanson and Thatcher (2020) have provided some insights into what the adaptation requirements for work systems might look like when designing for green jobs in the future, including working under extreme heat, exposed, and unpredictable conditions. As carbon dioxide levels move past scientifically determined tipping points, the climate systems will become more unstable meaning that almost every human-technology system will require adaptable and resilient characteristics in order to remain sustainable.

4.3.3. Designing for disaster management and planning systems

Dilling et al. (2015) predict that there will be circumstances where resilient, adaptable systems will be insufficient. In fact, some proposed adaptation measures have the potential to make the situation worse (e.g. cloud seeding). The predicted impacts of climate change include flooding from rising sea levels and extreme storms, heatwaves and wildfires, forced-migration, and drought and famine (IPCC 2021). In situations where mitigation and adaptation are insufficient, HFE can contribute to preparing disaster management and planning systems to cope with the consequences. HFE has already proposed (Moore and Barnard 2012; Thatcher, Waterson, et al. 2018) and has started to make inroads into assisting the preparation of disaster management systems including for COVID-19 (Sasangohar et al. 2020), rail incidents (Smith and Dowell 2000), and evacuations from Hurricane Katrina (Kirlik 2007). Clearly, HFE has the capabilities to provide valuable assistance for handling disaster and emergency situations arising from climate change and sustainability issues include sea-level rises, extreme weather events, pandemics, food supply shortages, mass migration, and other natural and human-made disasters.

4.4. Complex systems thinking issues

4.4.1. 'Scaling up' from local to global?

There are some synergies between the issues relevant for the sustainability global challenge and the societal thinking global challenge. Because the issues of sustainability and climate change happen at a global level, HFE needs to consider how mitigation and adaptation interventions might reach an appropriate number of people in the population. One route might be to assume that scalability would be achieved because interventions designed taking HFE into consideration would out-compete interventions that do not take the user into account (i.e. they would be easier and more intuitive to use, more effective in achieving performance goals, and more aesthetically pleasing to the user). However, there are also multiple other factors at play such as market dynamics, cost, and availability. In addition, a focus on free-market elements as the deciding factor may take too long and will not work in geographical regions where free-market economics is poorly (or not at all) accepted. Clearly, HFE has to develop other mechanisms to enable interventions that use sound HFE for sustainability to proliferate.

A number of authors in HFE have considered the scalability issue and all of them recommend that HFE requires a broader systems-thinking approach (Dekker, Hancock, and Wilkin 2013; Thatcher and Yeow 2016; Thatcher, Nayak, and Waterson 2020; Thatcher, Waterson, et al. 2018). However, broader systems thinking only tells us the general characteristics of leverage point possibilities, but does not provide specific details about where to find and how to identify those leverage points (Meadows 1999), and yet it will be particularly important for HFE to identify the points relevant to HFE that can contribute to interventions that can make a contribution at the global level. Using Gunderson and Holling's (2002) complex adaptive systems (especially the idea of panarchies) as a basis, Thatcher and Yeow (2016) have developed the sustainable systems of systems (SSoS) framework which might prove useful in identifying when and where to intervene using HFE (Thatcher and Yeow 2020), although the SSoS framework has undergone limited empirical testing and has not yet been used to identify leverage points (Thatcher, Metson, and Sepeng 2024).

4.4.2. Complex systems thinking tools

As a systems discipline (Dul et al. 2012; Karwowski 2005; Thatcher and Yeow 2016; Wilson 2000) with a human focus, HFE is ideally placed to contribute to the sustainability and climate change agendas.

However, as Thatcher, Nayak, and Waterson (2020) have already noted, while there are several complex systems analysis tools in the E/HF field (e.g. Accimap, CWA, EAST, FRAM, STAMP, STPA), it is highly likely that these tools have limitations when considering the complexity required to address sustainability and climate change issues. For example, Thatcher, Nayak, and Waterson (2020) looked at the feasibility of using Accimap, CWA, and STAMP and found that while these tools were fairly good at addressing issues of interconnectedness (even up to the planetary level as Salmon et al. (2019b) have shown), they were unable to deal with dynamic, adaptive, and self-organising systems and the property of emergence inherent in socio-eco-technical systems. Clearly considerable work needs to go into examining whether the other complex systems tools can address these issues, whether new tools need to be developed, or whether existing tools can be mixed, extended, or repurposed. Thatcher, Nayak, and Waterson (2020) suggest that mixing and repurposing of existing tools may be possible, but this is still an open question. Thatcher and Yeow (2016) SSoS framework provides a useful summary of the requirements for HFE interventions for sustainability, but while the SSoS framework might help identify the relevant properties for a sustainable HFE system, it has already been mentioned that SSoS has yet to be empirically tested. Finally, communicating systems thinking accessibility is also very important to tackle this important HFE grand challenge (Arnold and Wade 2015; Banerjee and Lowalekar 2021; Monat, Gannon, and Amissah 2022; Williams, 2021).

4.4.3. The role of context awareness and diversity

Diversity is key to the design of resilient systems. More forms and behavior-types give the system a greater chance to recover from unusual disturbances and hence supports sustainability. For this reason, Lange-Morales, Thatcher, and García-Acosta (2014) incorporated respect for diversity as one of the core values of HFE for sustainability. Diversity within the HFE discipline is often operationalized as cross-cultural design, but Lange-Morales, Thatcher, and García-Acosta (2014) have suggested that we need to go further and understand the diversity of place (i.e. the geographical and cultural setting) and ecological diversity (i.e. our interactions with other biological entities). As a consequence of global variability, Moray (1995) argued that few HFE solutions are truly universal. One way to foster diversity is to understand local context and to favor local solutions for local problems. As Thatcher and Yeow (2018) have noted, focusing on the local context not only increases HFE diversity, but also contributes to distributed HFE expertise and local employment. Local solutions are more likely to be accepted by local users as they have to live and work with the consequences of HFE interventions. There are numerous examples where a combination of foreign work practises and ill-considered technology transfers have left a complex array of working environments that seldom work as intended or no longer work at all. This forces HFE to focus on the context and to look at ways of involving local people in identifying and broadening the design solution options. For example, a considerable proportion of work worldwide actually takes place in the informal economy (Thatcher and Todd 2020) where traditional HFE seldom reaches.

4.5. Sustainability and climate change: education

We also need to consider how we will prepare students, practitioners, and university programs to effectively address the topics relevant to the grand challenge of sustainability and climate change. Dul et al. (2012) have already recognized that HFE needs to contribute to the discipline of sustainability and so we need to look at how we prepare HFE for this challenge. Understanding what and how to teach the relationship between sustainability/climate change and human behavior is a priority. Sterling (2001) provides an excellent coverage of underlying skills that should be taught to prepare for sustainability which includes the following concepts:

- Participation (the value of inclusion, participatory designs, cooperation, collaboration, and trans/interdisciplinarity)
- Complex systemic thinking (fuzzy borders between systems, the locality and the provisionality of knowledge, and emergence)
- Designing for change and adaptation (resilience and the design of resilient systems).

To deal with the challenges associated with the complex nature of climate change, the HFE systems perspective needs to be emphasized. Systems thinking has always been important to HFE. Dul et al. (2012) suggested that HFE should address issues at various system levels from a micro-level, to a meso-level, to a macro level. Wilson (2014) went so far as to state that any study, investigation, analysis, or development which did not take a whole system view was not HFE at all. Related to the notion of complex systems thinking, facts and actions should be the two main lines of focus for sustainability and climate change education.

Sustainability and climate change educators have been teaching factual information and building critical thinking and problem-solving skills. Monroe et al. (2019) identified two common themes of sustainability and climate change education: focusing on personally relevant and meaningful information, and using active and engaging teaching methods. Three types of knowledge are important as summarized by Monroe et al. (2019) from reviewing 49 climate change education programs: (1) changing people's attitudes about the importance of sustainability and climate change; (2) empowering action-taking by assessing the willingness to engage; and (3) encouraging selected sustainable behaviors. In particular, several authors have emphasized the need to broaden the HFE perspective to include an understanding of other disciplines such the humanities and the social sciences (Dekker, Hancock, and Wilkin 2013), while Moray (2000) envisaged including cultural studies and politics.

Our ethical stance within HFE also needs to be considered. Dekker, Hancock, and Wilkin (2013) initiated this discussion and Lange-Morales, Thatcher, and García-Acosta (2014) provided the first set of values for HFE and how we might seek to address sustainability and climate change issues. Thatcher, Nayak, and Waterson (2020) extended the issue of values to propose an integrated stance towards ethicality and sustainability in HFE. Thatcher, Nayak, and Waterson (2020) emphasized the necessity of working on education programs that teach about these values through teaching the goals of HFE, the underlying meaning of HFE, and the responsibilities of HFE. In this way, future HFE practitioners can put the values into practice to guide ethical behavior, so that it really plays a valuable role.

4.6. Teaching resilience, diversity, and context awareness

One advantage of adopting an HFE complex systems perspective is the inclusion of resilience characteristics in the design. Resilience refers to the features of a system that maintain normal operations, which means the system can automatically return to a 'normal' state if it accidentally or temporarily deviates from stability. Systems with resilience are called resilient systems. Woods (2015) has divided the different understandings of resilience into four categories: (1) resilience as rebound from trauma and return to equilibrium; (2) resilience as a synonym for robustness; (3) resilience as the opposite of brittleness; (4) resilience as network architectures that can sustain the ability to adapt to future surprises as conditions evolve. These various understandings of resilience in different application scenarios still need to be applied in the context of sustainability and climate change. For example, studies have shown that more exposure to nature can effectively boost the body's immunity. This is an example of physical resilience allowing the system (in this case a human) to rebound from mental trauma and return to equilibrium (Thatcher and Yeow 2018). In terms of architecture, resilient building is a concept that aims at creating progressive relationships between humans and their built environments (Thatcher and Yeow 2018), which allows for the achievement of energy conservation and environmental protection. Thatcher and Yeow (2018) suggested that diversity is one of the key properties to make engineered systems resilient while Thatcher, Nayak, and Waterson (2020) emphasized the need for adaptability.

Finally, the core element to ensure resilience is feedback. Feedback is an important concept which must be addressed with students from multiple perspectives including its history, models, and application. From an HFE perspective, feedback is about controllability; understanding what a system has done in response to a human action and then acting appropriately to correct the system if it is out of balance. Since feedback in natural open systems is complex and the goals of natural systems are indeterminate, this also requires education in understanding the various feedback mechanisms in complex systems, some of which may be impossible to determine from the outset. In these instances, the precautionary principle must be introduced (Johnston et al. 2007). Moray (1995) argued that HFE should design negative feedback control systems needed at all levels and time scales of society to control collective behavior that might be harmful to our communities or our environment. Hancock (2019b) suggested a more systematic discussion of feedback and proposed a basic model of feedback, composed of input, output, feedback, and information processing components. This model provided a theoretical basis for feedback, guaranteeing the resilience of the system and further enabling the ultimate goal of sustainability.

5. Grand HFE challenge: the future of education and training

5.1. Introduction to the future of education and training

According to the United Nations (2018), Sustainable Development Goal 4 should ensure inclusive and equitable quality education and promote lifelong learning opportunities for all. This goal promotes the reduction of disparities and inequities in education, both in terms of access and quality. We also need to consider how we will prepare students, practitioners, and university programs to effectively address the topics relevant to the grand challenge of sustainability and climate change. The HFE discipline and profession has a great potential to contribute to the design of effective educational systems (Kao 1976). However, the current impact of HFE on educational system design is still very limited (Legg 2007; Smith 2013). The related HFE research on educational systems has been mainly to physical and psychomotor phenomena (Bennett and Tien 2003; Díaz-López et al. 2022; Heyman and Dekel 2009; Smith 2007; Soltaninejad et al. 2021). Variability in student learning is prominently affected by the design of educational systems (Smith 2007, 2013).

5.2. Transformation of educational systems

The current digital transformation of educational systems has been driven by fast technological development and the disruption of the COVID-19 pandemic (Bonfield et al. 2020; García-Morales, Garrido-Moreno, and Martín-Rojas 2021). While the attention of a dedicated teacher is difficult to replicate, digital technologies can deliver individualized curriculum, pacing, and information design (Wallace et al. 2022). The opportunity exists to design resilient, accessible educational systems with which to reach a much larger proportion of the world's population. Augmented reality (AR) and virtual reality (VR) have the potential to make digital learning more immersive and experiential, but have not yet been fully leveraged (Cheng, Yang, and Andersen 2017; Chessa and Solari 2021; Liao et al. 2019). Artificial intelligence (AI) has enabled a variety of adaptive learning supports, such as personalized tutoring (Haensch et al. 2023; Kasneci et al. 2023).

Table 4 summarizes the impact of the digital transformation of education and training. The role of teachers change from *Sages on the Stage* to *Guides on the Side* (Chung 2005; Jones 1999; King 1993; McInnerney and Roberts 2009; Sherry 1995), and sometimes to *Host with the Most,* e.g. deliver teaching to a large audience in a virtual classroom (Strawser 2022). Learning facilities used to be classroom centric but are becoming location agnostic. Steadily increasing overhead costs are being trumped by high quality, low-priced providers, providing whole degrees for less than $10,000 (Christensen et al. 2020; Oprisko and Caplan 2014). Society has become less enamored with credentials compared to competencies.

The current design of most online learning systems favors cognitive learners who prefer concrete, logical and sequential information (Boy 2013). Social presence of peer learners may not be equally desired for different learners (Chen et al. 2020). The new generation of students as 'digital natives' have a strong tendency to multitasking during learning, even in

Table 4. Contemporary vs. future environment for education and training.

	Contemporary environment	Future environment
Students	Compliance oriented	Sophisticated consumer
Teachers	Sage on the stage	Guide on the side
Facilities	Classroom-centric	Location agnostic
Technologies	PowerPoint, Internet	Immersive media, AI, big data, smart environments
Administration	Increasing overhead	Decreasing overhead
Society	Credentials oriented	Competencies oriented

classrooms (Reyes et al. 2021; Tassone et al. 2020). The introduction of digital technology does not guarantee effective learning (Kreijns, Kirschner, and Jochems 2003). Learning performance may not be improved, and sometimes degraded (Mayer, Makransky, and Parong 2022; Oberdörfer and Latoschik 2019). Massive Online Open Courses (MOOCs) can result in learners having difficulties staying engaged and the completion rate is low (Paton, Fluck, and Scanlan 2018). In a recent study of college students' experience with online learning during the pandemic (Patricia Aguilera-Hermida 2020), students reported such negative outcomes.

Global education rates presently lag the United Nation's 2030 *Sustainable Development Goal 4. Needs And Capabilities In Education And Training* differ by individual and locale, as do fundamental pedagogical traditions and available infrastructure (Chan, Bista, and Allen 2021). Different countries provide very different landscapes for the proliferation of change. For example, each school district in the US can vote to change the local curriculum, but the central government in China can decide to change the curriculum nationally. Cultural norms and traditions also modify the meaning of good learning behaviors, e.g. passive and compliant learners are more appreciated in collectivism cultures than in individualistic cultures (Chugh and Ruhi 2018). Education is unevenly distributed along many comorbid dimensions: geography, race, gender, and socio-economic status (Alomari et al. 2020; Miles and Singal 2010; United Nations 2018).

The importance of teachers and their guidance in learning should not be overlooked (Fischer and Hänze 2019). Yet it is necessary to re-define the role of teachers in ways other than 'experts' (Reyes et al. 2021). Assessment and selection are aspects of pedagogy that will be affected. Standardized tests have become optional in developed countries (see Soares 2015). Machine learning, without careful design, can be racist, sexist, and blind to need (Zou and Schiebinger 2018).

5.2.1. Importance to HFE discipline & profession

HFE research is needed to better understand individual differences and design features of digital learning environments. Possible negative influences of digital technologies include information overload (Buglass et al. 2017; Parry and Le Roux 2019; Stephanidis et al. 2019). We need to ensure real learning and personal growth, as well as mental well-being (Murphy, Moore, et al. 2017). Effective collaboration has not been addressed in current curricula (Wartman and Combs 2019; Long and Magerko 2020). A careful balance between automation and augmentation is needed to avoid negative impacts on learners' critical thinking and problem-solving skills (Rouse and Spohrer 2018). Human-centered design (HCD) should employed to design systems around human needs, capabilities, and constraints (Boy 2013). Multiple HFE methods for job and task analysis are available to embed HFE principles in healthcare education (Vosper, Hignett, and Bowie 2018). Changing job requirements and necessary training to cope with these changes often lead to stress and workload needs among teachers (Woodcock 2007).

5.2.2. HFE strategy for success

Design practices need to begin with user experience (UX) followed by user interface (UI) and then functional design and technology selection. The result, as Smith (2007) advocates, will be the integration of HFE with educational psychology. As Woodcock's early experience (2007) shows, these elements of HFE can be taught in primary and middle schools, but the concepts of HCD are not easy to understand for young children.

5.2.3. Ramifications for developing countries

Roughly 85% of the global population has smart phones. Thus, information technology can provide inclusive and inexpensive access to quality education in developing countries. Such access can be limited due to infrastructure and cost issues (Bahati 2015; Harran and Olamijulo 2014). Solutions need to be modified to suit local conditions and to address local education needs, in addition to language translation and cultural adaptation. HFE research in physical aspects of educational systems are still relevant in developing areas where teaching and learning facilities are less than adequate (Odunaiya, Owonuwa, and Oguntibeju 2014). Furthermore, the awareness of HFE is low in many developing countries (Chedi and Mustapha 2020; Naeini and Mosaddad 2013).

5.3. Computing to fundamentally change education and training

Studies have shown that format variations, such as typeface and spacing, significantly influence reading effectiveness (Beier et al. 2022; Wallace et al. 2022), factors that are now infinitely flexible (Sawyer 2024). The application of large language model technologies in readability research further enhances the potential for personalized learning (Sawyer 2024). Additionally, the use of artificial <u>intelligence in educational platforms can offer adaptive learning paths (</u>Zawacki-Richter et al. 2019<u>). The</u> integration of spatial computing and augmented reality (AR) can provide immersive learning experiences (Merchant et al. 2014). All of these technologies facilitate the creation of extensive data sets, revealing patterns in performance, and preference (Berninger et al. 2017). These technologies for education and training provide opportunities that align with HFE principles of user-centered design (Karwowski 2005). Traditionally, readability focused on tailoring content, with format being a static element (DuBay 2004). However, as Sawyer (2022) highlights, in digital reading environments, both content and format are malleable and can be individuated. Content can now be generated on-the-fly (Moore et al. 2023).

5.3.1. Exceeding traditional methods by improving learning and performance

The role of HFE is crucial to the transition from traditional pedagogy to individualized education, including educational technologies that are intuitive and user-friendly (Karwowski 2005). For example, adaptive learning technologies will tailor educational content to the learner's state (Aleven et al. 2017). HFE can build such systems (Hancock, Sawyer, and Stafford 2015; Hamari, Koivisto, and Sarsa 2014; Sawyer & Hancock, 2018), adjusting to each learner's pace to achieve performance goals (VanLehn 2011) and distinguishing between looking and seeing (Krueger et al. 2019), boredom and exhaustion (Sawyer & Hancock, 2018), possibly identifying error-inducing designs (Hancock and Sawyer 2015).

5.3.2. Retaining the human element of enhancing competency and tailoring support

Will the human remain in this loop (Sawyer et al. 2021)? By adapting to the learner's evolving needs (Aleven et al. 2017), such systems might act like a human educator, discerning the needs of their pupil (VanLehn 2011), but they could also act with a human educator. Intelligent systems, predictive analytics, and adaptive learning technologies (Sawyer et al. (2021) are the means to this end.

5.3.3. HFE strategy for success

HFE is underrepresented in educational technology, and sometimes fails to provide the training to work with advanced technology (Hannon et al. 2020; Rantanen et al. 2021). Integration in needed to enable the crafting of educational environments that are both adaptive and personalized (Sawyer et al. 2021).

Collaboration with other design disciplines should be a central strategy. AI-driven technologies are increasingly shaping the future of curricula by enabling adaptive, real-time learning environments that cater to the evolving needs of interdisciplinary professionals. One notable example is the U.S. Navy's Ready Relevant Learning (RRL) program, which utilizes AI to create personalized and adaptive training experiences tailored to individual performance. The RRL initiative demonstrates how AI can dynamically adjust to user interactions and cognitive load, providing real-time feedback that enhances decision-making skills in mission-critical environments (U.S. Navy 2020). By integrating AI into such learning platforms, professionals can be better prepared to engage with complex systems, developing the cross-disciplinary skills necessary for rapidly evolving technological landscapes. The implementation of AI within these training environments ensures that HFE curricula remain relevant and aligned with the demands of industries where human-machine collaboration is increasingly essential.

5.3.4. Ramifications for developing countries

The democratization of personalized learning has the potential to bridge educational divides, providing equitable access to quality education (UNESCO 2020). HFE initiatives need to empower local educators and learners with the tools to innovate within their contexts (Sawyer 2022).

5.4. Beyond classrooms

The *Future of Education and Training* challenge has two components: life-long learning, as well as education, and training for the skilled technical workforce. It is becoming necessary for people to keep their knowledge current in this fast-developing era. Outside of classrooms, people at different ages are self-educating themselves by reading related articles, watching TED talks, or taking courses provided by their employers, traditional educational institutions (e.g. most MOOC courses) or by other users (e.g. skillshare.com). There is a tendency to focus on education and training for college bound students, often with an emphasis on STEM disciplines. This is obviously important, but there is another population whose education and training needs focus on competencies to manufacture, operate, and maintain societies' increasingly complex systems. This is the skilled technical workforce (Autor, Mindell & Reynolds, 2021). Indeed, two of the fastest growing job opportunities in the US are in the solar and wind industries.

5.4.1. Life-long learning and design of educational systems

Fischer (2000) pointed out that lifelong learning, defined as *a mindset and a habit for people to acquire*, is an essential challenge of societies worldwide, as evidenced by accelerating changes in the nature of work and corresponding educational requirements. Furthermore, lifelong learning creates the need to understand, explore, and support new essential dimensions of learning that include (1) self-directed learning, (2) learning on demand, (3) collaborative learning, and (4) organizational learning. This need is due to the certainty of change during a professional lifetime, which necessitates lifelong learning. Also, the increasing demands of 'high-tech' jobs require support for learning on demand. However, as Van Merriënboer et al. (2009) pointed out, lifelong learning is not reaching its full potential because the currently used approaches to lifelong learning are too fragmented and are based on formal approaches to learning that were directly adopted from traditional education systems. Recently, de Lima Flauzino et al. (2022) reviewed the practical actions of the lifelong learning paradigm and concluded that there is an imbalance between lifelong learning activities for older adults in the formal, non-formal, and informal modalities and that the lifelong learning paradigm has to be incorporated into practical actions by different conceptual generations.

Van Merriënboer et al. (2009) argued that the changes in working, living, and learning influence the need for lifelong learning, supporting an individual's health, development, and life enrichment. The key to the design of effective lifelong learning strategies is the knowledge about (1) how people and organizations/regions adapt and change to meet present and future challenges, (2) how individuals, groups, and organizations/regions can make use of learning opportunities to bring greater fulfillment to their life, and (3) under what conditions they have the motivation and disposition to continue to learn. Care et al. (2018) discussed the need for the education system to align with 21st-century skills to overcome concerns about global inequities and lack of fairness, especially with respect to the need for developing transferable skills and competencies for all children and youth worldwide. They also cautioned that global, regional, and national efforts to expand the learning agendas have yet to translate into their full-scale implementation at the school and classroom levels.

Since life-long learning is a key issue for the knowledge society (Klamma et al. 2007), its impact on professional learning, learner competence, and the social networking that supports efficient life-long learning should be carefully considered (Charokar and Dulloo 2022; Neely et al. 2006). HFE professionals can contribute to addressing all the above challenges by developing design guidelines for educational systems supported by the new media and innovative computational technologies to ensure effective solutions to these challenges.

5.4.2. Importance to HFE discipline & profession

To support such less formal but more common learning tasks, HFE effort is needed to guide system design to support extraction of knowledge from a massive amount of information, to form a sustained personal knowledge base, to provide visualization and other options for exploring associations among knowledge elements to form new insights, and to handle misinformation and disinformation from the internet. HFE has a long history of designing effective training systems. In particular, job and task analyses will be central to optimizing employers' training investment. Of particular importance will be designing and integrating the components of training provided by high schools, community colleges, and employers.

Reuse of content across employers' domains will enable attractive economics for these programs.

5.4.3. HFE strategy for success

All aspects of this challenge can benefit from the same strategy. HFE needs to expand its purview and partner with other disciplines. In particular, HFE needs to lead the application of human-centered design to overall training systems, partnered with subject matter experts as well as educational psychology, industrial design, and computing. Rapid advances in artificial intelligence are changing the nature of work. This presents both opportunities and challenges for HFE practitioners, including the emergence of new industries and occupations and elimination of some traditional professions. Smart solutions are needed to ensure better *Education and Training* that can align available domains and the future workforce's skills. Training programs designed to gain AI and advanced information technology capabilities must improve their availability and content. The evolution of education and training needs to keep one overall goal in focus.

The purpose of education and training is to enhance people's potential to perform by providing them the knowledge and competencies to compete in the global marketplace while also contributing to their families, neighborhoods, and communities. We should not assume that status quo pedagogy and technology will persist. The nature of education and training will substantially change. HFE should assure that this evolution is human-centric for students, teachers and the many other stakeholders involved. The technology is an enabler, not an end in itself. In the process, we need to attend to the deeper phenomena that affect education and training outcomes. Economic and social factors, as well as health, effect students' abilities to focus on learning. We need to provide the support infrastructure to assure that such factors are mitigated.

Table 5 summarizes this grand HFE challenge in terms of needs and challenges at all levels of the ecosystem and for all types of learning.

5.5. Ramifications for developing countries

The grand challenge of *The Future of Education and Training* stipulates the need for a greater understanding of behavioral economics across borders (Afif et al. 2019; Berndt and Wirth 2019; Lavecchia, Liu, and Oreopoulos 2016; Marginson 2010), assuring students productive relationships with information technology, developing educational processes that enable individualized pedagogical capabilities, and human-centered design for special populations worldwide (Forsythe and Venter 2019). Applications in developing countries should focus

Table 5. Diverse needs and challenges of different types of education and training.

	Changes in societal needs	Changes due to technology	HFE needs & challenges
K-12	Need curriculum & experiences to prepare students for college; need for flexible, valid, and equitable assessment and selection	Education capabilities much broader than classrooms & screens; effectively interacting with technologies becomes a new education need	Understanding behavioral economics of student behaviors; providing both pedagogical content and tools to help students' establishing healthy relationship with information technologies
College	Need to support students for retention & success; stronger need for cultivating critical, creative, and inter-disciplinary thinking	Education capabilities much broader than classrooms & screens; knowing how to work with augmented cognition (e.g. AI) is a new education need in many disciplines	Human-centered design of processes & supports
Skilled technical workforce	Need people to manufacture, operate, and maintain complex systems	Technology is driving needs for greatly increased technical skills	Determine balance between classroom and hands-on training
Continued professional development	Need to enable continuous learning & retention, and to handle information overload and misinformation from online	Technology is pervasive but poorly vetted and often outdated	Human-centered design of life-long learning supports
People with disabilities	Need to enable mobility & productive employment	Technology is promising but seldom rigorously evaluated	Human-centered design for people with disabilities
Older adults	Need to enable mobility & aging in place	Technology is promising but seldom rigorously evaluated	Human-centered design for older adults

on adopting what others have developed and proven. Tailoring to language, alphabet, and culture will likely be a challenge but much if not most pedagogical content, e.g. rules of algebra, will remain applicable. The emphasis for these applications will be adoption and adaptation rather than design.

6. Grand HFE challenge: the future of personalized health

6.1. Introduction to the future of personalized health

Human healthcare is perhaps our single most important public endeavor. It affects each one of us and is one of the largest expenses of our federal government (Carayon 2021). Healthcare is constantly evolving and making use of new technologies, which can bring great benefits but also increases the fragility and complexity of care (Ahamed and Farid 2018; Baig, GholamHosseini, and Connolly 2015). In the context of personalized health, our healthcare systems have both an admirable and challenging (Snell, Briscoe, and Dickson 2011). With regards to the latter, the success rates for major diseases are still relatively poor. One potential reason for this result is that we tend to treat isolated illnesses. Yet, humans are complex systems such that multiple isolated illnesses can trigger a cascade of events that result in a chronic major illness. It is generally agreed that there is both a need and opportunity to change our approach, or at a minimum to complement it, from a focus on treatment (healthcare) to one on prevention (wellness) using modern bio-information technology (aka 'big data'). This signifies a departure from traditional models of one-size-fits-all medicine to an era where healthcare is uniquely tailored to the individual. Such a shift will allow us to be more proactive, to better understand how our behaviors influence our health, and to control and manage our wellness rather than react to our health problems. HFE principles guide the design, implementation, and optimization of healthcare and biotechnologies, ensuring their usability, effectiveness, and practicality in real-world healthcare scenarios. The collaboration between clinicians, engineers, and HFE is essential for unlocking their full potential at the forefront of healthcare advancements (Hignett et al. 2013).

Healthcare has historically followed a reactive model, focusing primarily on treating illnesses once they manifest. This is also done with generic treatments, based on generalized models of illnesses. However, the limitations of this approach are increasingly apparent, prompting a paradigmatic shift towards proactive and personalized health strategies. *The Future of Personalized Health* encompasses a holistic view of individuals, considering their genetic makeup, lifestyle, environment, physical space and unique health trajectories. In this future landscape, advanced technologies, particularly those driven by HFE principles, play a pivotal role (Cruz-Correia et al. 2018; Gray 2007; Waterson and Catchpole 2016). From wearable devices and sensors to data analytics and artificial Intelligence, these innovations empower individuals to actively engage in managing their well-being (Qi et al. 2017). The integration of big data and bio-information technologies enables a comprehensive understanding of how individual behaviors influence health outcomes, fostering a shift from a mere focus on healthcare to a broader emphasis on wellness and prevention (Cutica, Mc Vie, and Pravettoni 2014) Amidst these advancements, this HFE grand challenge unfolds, presenting an opportunity to harness the expertise of HFE professionals to realize the benefits of personalized health care (Gray 2016; Yang et al. 2016). The challenge is multi-faceted, encompassing the design of user-friendly technologies, optimizing human-machine interfaces, considering the diverse cultural and contextual factors influencing health, and ensuring ethical and responsible implementation.

Below, we describe five main challenge areas for the future of personalized health, with a focus on technology and wellness. These challenge areas start with a focus on movement, a fundamental need for any work activity, and an independent lifestyle (Challenge area #1). This is followed by a focus on our aging population and the need for new healthcare technologies to be designed for generations that need them most (Challenge area #2). We note here that the middle-aged individuals living at this time will constitute the older population of the future. A natural next step is the ethics and privacy management (Challenge area #3). We then highlight the need for attention to the physical environment and process design in healthcare settings, in order to improve outcomes for personalized interventions (Challenge area #4). Finally, we end with the challenge area of integrating the brain into the healthcare system, from design of healthcare tools to utilization in clinical settings (Challenge area #5). We believe that each of these challenge areas in 'The Future of Personalized Health' can and should have major contributions from and to the field of HFE.

6.2. Challenge area #1: development of phenotypes based on understanding causal pathways for musculoskeletal disorders (MSDs)

Musculoskeletal Disorders (MSDs) constitute the number one disabling health condition throughout the world (Marras and Karwowski 2021). These conditions not only limit the ability of people to participate in productive work, but they also can negatively impact the quality of life and lead to comorbidities that could have devastating consequences. Low back disorders are the number two reason for opioid prescriptions the United States which can lead to opioid use disorders. Unfortunately, once MSDs become chronic the conditions could last for extraordinarily long periods of time. For example, the average length of a chronic low back disorder is 7 years. Diagnoses and prognoses for MSDs are currently problematic. Since MSD pain is subjective and difficult to measure it is difficult to understand the root cause of the disorder. A physiological source of the disorder is often not possible to identify. Without a root cause, treatment then becomes difficult to prescribe. For example, imaging (MR, X-Ray, CT) of the spine is inconclusive for the vast majority (over 80%) of low back pain sufferers. To make matters worse, when imaging anomalies are identified, it is difficult to distinguish between natural aging and structural irregularities that would lead to pain. Therefore, many complex MSDs (e.g. spine problems) are treated with a trial-and-error approach, typically beginning with the most conservative treatments and then ending with surgeries that are often not successful. Another problem with the trial-and-error approach is that the longer a person experiences pain, the more likely it is that the MSD becomes a chronic illness. This is because pain pattern responses are established in the brain and can be active even when the initial stimulus has resolved. Thus, it is important to understand the root cause of the disorder and treat the disorder as soon as possible.

MSD causal pathways are complex and multidimensional. It is generally accepted that MSDs are influenced by a mixture of biopsychosocial factors along many dimensions. Thus, there are many mixtures of factors that can lead to these disorders and a complex mix of these dimensions also can influence the recovery from the disorder. The mind-body nature of biopsychosocial factors makes the understanding of the causal pathways particularly difficult to understand. Therefore, the ultimate challenge area for MSDs becomes an actionable understanding of this biopsychosocial complex mind-body system. This is a monumental undertaking. Towards achieving this goal, one can envision several necessary aims. First, since the biopsychosocial dimensions are so multidimensional, it will be necessary to create a very large data set so that all aspects of the biopsychosocial system can be parameterized. Existing medical data sets are typically established exclusively for billing purposes (e.g. ICD-10 codes) and, thus, do not lend themselves to scientific discovery. In addition, it will most likely be necessary to greatly improve the level of quantification of most measures associated with MSDs. Thus, instead of categorical descriptors of the various dimensions of MSDs it will be necessary to establish quantitative, continuous metrics that can be better assessed by advanced analysis techniques.

Second, longitudinal or prospective data sets that monitor the various significant components of the biopsychosocial model will be necessary. Here again, given the high dimensionality of the biopsychosocial model, these data sets need to contain massive amounts of data and records from hundreds of thousands of participants. Finally, one needs to consider how to make sense out of the massive amounts of 'big' data that will be collected. Artificial Intelligence (AI) and Machine Learning (ML) techniques provide potential mechanisms to reveal patterns that would be extremely difficult to identify any other way. However, the results of such analyses might help identify patterns in the biopsychosocial data but would not necessarily assist us in understanding the workings of the causal pathways that would be necessary for actionable clinical decision making. However, these techniques could assist in identifying the focus for theoretical model building for further, deeper analysis and facilitate explainable AI efforts (Viceconti, Hunter, and Hose 2015; Vashist, Schneider, and Luong 2014). Collectively, these efforts will help us understand the biopsychosocial interactions within the population that lead to MSD development and resolution. These efforts should facilitate targeted actionable personalized medicine treatments and preventive technology.

6.3. Challenge area #2: optimizing health technology for the aging adults

It is well known that our population is aging (Kanasi, Ayilavarapu, and Jones 2016; Kulik et al. 2014; Sanderson and Scherbov 2007). Today, there are more people over the age of 65 than ever before. And the race is on to make use of modern technology in the development of devices, applications and tools to support the aging adults. For example, there are numerous connected devices that can monitor their health and wellness and report to family and physicians alike. There are smartphone applications that can improve their memory and cognitive function (Sharon 2017). There are wearable devices that can reduce tremors. There are even home robots that can serve as a friend, mental health support, or assist with daily living tasks. Ironically, though, while the aging adults can greatly benefit from health technology, they, as a group, are least likely to adopt, or effectively use new technology. Anyone who has tried to help their aging parent pair a Bluetooth device, download and setup a smartphone application, change settings on their smartphone, or troubleshoot a computer hardware problem knows this all too well. Too often, the design of health technology requires technological sophistication and demands significant cognitive resources of the user. We must develop design solutions that require little memory.

As the aging adults have difficulty using technology designed to help them, one of the biggest challenges facing society is the development of health technologies that can actually be understood, adopted, and effectively used by the aging adults. This challenge is, by nature, a design problem and thus it is particularly suited for the human factors discipline (Fisk et al. 2020; Smith 1990). HFE emphasizes a user-centered design approach, understanding the unique needs, abilities, and limitations of aging adults. This involves considering factors such as cognitive decline, motor skills, sensory impairments, and preferences in the design of health technologies (Cohen et al. 2022; Mirelman et al. 2017).

Addressing this challenge will require coordination among product engineers, researchers in aging, technologists, healthcare providers, and HFE professionals, and must address both the design and psycho-social aspects of technology adoption and use. The successful solution approach will take into account accessibility and inclusivity. HFE specialists focus on making health technologies accessible to individuals with varying levels of physical and cognitive abilities (Carayon 2021). This includes designing interfaces that accommodate visual and hearing impairments, providing alternative input methods, and ensuring overall inclusivity. HFE can contribute to the development of technologies that promote independence and autonomy among aging adults (Healey 2022; Wooldridge, Carman, and Xie 2022). This includes designing tools that assist with daily living activities, monitor health parameters, and facilitate communication with healthcare providers while respecting the user's sense of control (Ahmad et al. 2022; Klasnja and Pratt 2012). We have the health technology to detect and predict diseases, monitor vital signs and even mitigate adverse events (Dwivedi et al. 2022; Yang et al. 2019). Solving this challenge area will enable us to take advantage of the increased life span present in society. HFE acknowledges the importance of social and emotional well-being in older adults and all segments of our community (Elder and Clipp 1989; Salmon et al. 2022b). Technologies should be designed to facilitate social connections, provide mental health support, and address potential feelings of isolation that can accompany aging (Peute et al. 2022). HFE can fosters and lead interdisciplinary collaborations, bringing together designers, healthcare professionals, gerontologists, and technology experts (Carayon 2021). This collaborative approach ensures a holistic understanding of the needs of aging adults and results in comprehensive health technology solutions (Tsekleves and Cooper 2017). In essence, HFE should provide guiding principles to create health technologies that not only cater to the physical and cognitive aspects of aging but also enhance the overall well-being and quality of life for older individuals (Czaja 2016; Carayon 2021; Hignett et al. 2013; Srinivas, Cornet, and Holden 2017).

By prioritizing user needs, promoting inclusivity, and considering the social and emotional dimensions of aging, HFE can contribute to the development of technologies that empower and support aging adults in their healthcare journey.

6.4. Challenge area #3: managing ethics and privacy

An underlying theme of the two aforementioned challenge areas is the expectation that technology will yield massive amounts of data about human health, lifestyle activities, and even medication taking (Chawla and Davis 2013; Qadri et al. 2020; Roehrs et al. 2017; Yang et al. 2016). For example, as one enters a healthcare facility or visits a doctor, data about one's health status may be transmitted to several sources. While such data gathering and sharing presents a tremendous opportunity, it comes with ethical and privacy issues (Abouelmehdi, Beni-Hessane, and Khaloufi 2018; Verma et al. 2022), not to mention cybersecurity concerns (Crigger et al. 2022; Chang and Wei-Liu 2022) that represents a significant challenge to be addressed (Ahamed and Farid 2018; Yaqoob et al. 2022; Zaaba et al. 2021). What if your health information was constantly being scanned, monitored, utilized, and perhaps even sold as you move through the world? Imagine that your automobile knows about your level of fatigue, nutrition, hydration, blood alcohol level, and more. Imagine your doctor knows every substance in your bloodstream, whether prescribed, over-the-counter, or illicit. Imagine your insurance company knowing when you take (or miss) your medication. Imagine that your web browser presents products to you, not based on your search history but on your actual state of health and general wellness.

Significant research efforts are being undertaken on the consequences of human health, fitness, and lifestyle data being shared with insurance companies, healthcare providers, family and friends, and perhaps the public (Scobie and Castle-Clarke 2020; Semantha et al. 2021). Notable examples include the work conducted in the UK by the Turing Institute, Ada Lovelace Centre for Data Ethics and Innovation at Oxford, or research conducted in the United States by the Office of Science Policy of the National Institutes of Health (NIH) and dedicated academic centers, such as the Berkman Klein Center for Internet and Society at Harvard University, the Center for Biomedical Ethics at Stanford University, The Berman Institute of Bioethics and the Johns Hopkins University Information Security Institute, or the Center for Long-Term Cybersecurity at UC Berkeley. The above institutions not only study the issues of health data privacy and ethics but also lead in the development of best practices and national and international policy guidelines and regulations (Dove and Phillips 2015; LaMonica et al. 2021; WHO, 2007). Many recent studies address several critical questions related to the benefits of health information dissemination, given the ethical and privacy concerns (Attaran 2022; Shi et al. 2020) or the level of control that citizens will have over their health information. These questions must be answered for us to truly reap the benefits of connected devices, health telemetry, blockchain, and related technologies (Abbas et al. 2016; Haleem et al. 2021; Siyal et al. 2019; Yang et al. 2016). The challenge is twofold: First, we must identify ways to provide transparency and control to individuals whose health-related information may be transmitted to or shared with others (Vlahou et al. 2021). Second, we must develop guidelines for the ethical use of health information (LaMonica et al. 2021) such as the General Data Protection Regulation in the European Union (Voigt and Von Dem Bussche 2017), or the California Consumer Privacy Act in the United States (Mulgund et al. 2021).

6.5. Challenge area #4: reduce risks of injury from healthcare settings and providers

Hospitals are chaotic, complex environments. It has long been known, since Lucian Leape's seminal work on medication errors (Leape 2009), 'To Err is Human', published by the *Institute of Medicine* in 1999, that when in a healthcare setting you are as likely to be harmed by a mistake as you are to be cured by a successful intervention (Kohn et al. 1999). That may be a bit of an overstatement, but while this report changed widely held perceptions about the safety of health care in the United States, today little has changed about the underlying factors that contribute to medication errors and other 'mistakes' made by healthcare providers. The recent case of Radonda Vaught, a nurse who was convicted of criminal charges for mis-dosing a patient, has brought the disfunction of healthcare settings to the forefront (Sofer 2019). And, while new technologies bring great promise to the health care arena, there is some evidence that blindly adding technology to an otherwise archaic system, such as the typical hospital, may only increase the propensity for mishaps. The time is now to take on the challenge of reducing healthcare induced errors. We can no longer stand by and watch preventable adverse events repeat themselves.

The challenge is to design a healthcare setting such that it is resilient to medication errors and other types of health delivery mistakes. Such a challenge demands a multi-discipline, systems engineering approach that addresses a wide range of issues to include, but not limited to: work shifts, workload, staffing levels, product and system design, training, policies and procedures, technology integration, and organizational culture. It must focus on the latent preconditions for medication and other types of errors commonly made in hospital settings. It must also make better use of data on adverse events, as well as close calls/near misses. And, to sustain improvements in the aforementioned factors, we should include the adoption of HFE professionals embedded in hospital settings as common practice.

HFE adopts a system's thinking approach to healthcare, recognizing that risks of injury often stem from complex interactions within the healthcare system. By analyzing the entire healthcare delivery process, from patient admission to discharge, This challenge area requires identification of potential points of failure, communication breakdowns, and system vulnerabilities that may contribute to injuries. As healthcare increasingly incorporates advanced technologies, HFE addresses the integration of these technologies into the workflow. This includes designing user-friendly interfaces, providing adequate training for healthcare professionals, and ensuring that technology enhances, rather than hinders, the delivery of personalized care. Patient safety is closely tied to effective communication and teamwork among healthcare providers. HFE interventions aim to improve communication channels, encourage collaboration, and establish clear protocols for information sharing. This is particularly crucial in personalized health, where individualized treatment plans require seamless coordination among multiple healthcare professionals. The physical environment of healthcare facilities is a critical factor in patient safety. HFE considers the design of patient rooms, waiting areas, and other spaces to minimize the risk of falls, infections, and other adverse events.

Personalized health interventions may require specific adaptations in the physical environment, and HFE should ensure these are implemented safely. For example, in recent years, there has been an important transition within the healthcare industry as more healthcare tasks and activities that used to be done in medical facilities are now being performed in home environments by both professionals and family members or others who are not trained caregivers (NRC, 2011). The Report by the NRC Committee on the *Role of Human Factors in Home Health Care* outlined several critical issues to ensure appropriate accommodations for both care recipients and caregivers concerning diversity, strengths, and human limitations. It provided specific recommendations for improvements in home healthcare, including (1) healthcare technologies, medical devices, and health information technologies involved in healthcare in the home; (2) caregivers and care recipients; (3) residential environments for healthcare; and (4) research and development needs.

6.6. Challenge area #5: bringing the brain into the loop of healthcare

There is an unmet need for continuous, safe, and accessible brain function assessment for routine use in healthcare, spanning from diverse psychiatric conditions to developmental and neurological disorders.

Similar to measuring cardiac function (i.e. heart rate and blood pressure), tools and approaches are needed to enable practical and rapid measurement of brain function as additional vital signals for clinical triage as well as assessment of performance and mental state. Early evidence related to the importance of specific brain regions for complex cognitive processes such as language and memory, came in the nineteenth century from case studies of patients with localized brain damage (Vaidya et al. 2019). Using limited tools and data, clinical researchers at the time, were able to identify dissociable components for many complex brain processes that depend on networks of localized brain regions. Following those initial findings, brain lesion studies of humans (after a traumatic brain injury, tumor or other damage) and non-human animals (after induced lesions) provided fundamental insights into brain function models and inspired decades of new ideas related to the neural activity basis of cognitive, perceptual, motor processes and complex behavior. For more than a century, psychiatrists have known that mental illnesses are essentially due to disruptions of typical brain activity (Andreasen 1988). However, clinicians lacked the tools and methods for routine triage of brain function for diverse brain disorders.

The next big milestone towards this goal was the development of non-invasive brain imaging technologies during the last decades of twentieth century. These new tools such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET) were room-sized, costly and restrictive, but enabled increasing research to catalog anatomical (structural), metabolic, and rhythmic (functional) abnormalities in diverse brain disorders as well as typical brains during perceptual, motor, and cognitive operations (Kotz, Ravignani, and Fitch 2018; Posner et al. 1988). The following decades have resulted in the exponential growth of research stimulating new interdisciplinary research fields all related to brain studies.

The opportunity to unravel brain processes and tackle the paramount puzzle of theoretical modeling of the brain, as well as the diagnosis, prevention, and treatment of brain disorders starts with measuring the functioning brain. These ultimate challenge areas have been recognized nationally and internationally with the launch of dedicated 'brain initiatives' in many developed countries such as the United States BRAIN initiative and Europe's Human Brain Project, and then at grand scale worldwide in 2010s (Grillner et al. 2016). Existing studies with traditional neuroimaging approaches have accumulated overwhelming knowledge but are limited in scope (i.e. only in artificial lab settings and with simplified tasks). Hence, measuring the brain activity in a diverse array of everyday tasks is an urgent and is needed to move neuroengineering and neuroscience to the next level; that is to enable practical clinical and translational research that will form the basis of an entire new industry of neurotechnologies (Ayaz and Dehais 2019). As an interdisciplinary new field, neuroergonomics aims to fill this gap: Understanding the brain in the wild, its activity during unrestricted real-world tasks in everyday life contexts, and its relationship to action, behavior, body, and environment (Dehais, Karwowski, and Ayaz 2020).

Recent advances in neuroscience and engineering have allowed increasingly accessible, mobile and wearable neurotechnologies that can record or alter human brain activity in natural everyday settings (Ayaz and Dehais 2019). Following significant conceptual and methodological improvements within the last decades, portable neuroimaging sensors, electroencephalography (EEG), and near-infrared spectroscopy (NIRS) are now widely adopted to study the neural mechanisms underlying human perceptual, cognitive, and motor functioning with a focus on real-world contexts. EEG and NIRS record complementary correlates of brain function, electrophysiological activity, and cortical oxygenation changes, respectively.

Portable neurotechnologies have already demonstrated exceptional potential and are poised to transform all aspects of our daily lives (Gaudry et al. 2021). For example, a new NIRS-based medical screening tool became the first handheld system for traumatic brain-bleeding detection, that could only be done before using room-sized computerized tomography (Ayaz et al. 2019). With this handheld NIRS, brain scans of patients can now be taken at the site of an accident, in the ambulance, and repeatedly within the hospital. This new generation mobile NIRS system is currently deployed in 42 countries/6 continents in both civilian and military hospitals, and has already become the standard of care for children and sports medicine in some European countries. Capitalizing on the rise of mobile neuroimaging, psychology, and other related disciplines, neuroergonomics theory and research could help expand our understanding of the human brain function, and its use for improving complex machines, work environments, and eventually clinical processes for diagnosis, treatment, and even prognosis in the upcoming decades.

By integrating the brain into the loop of healthcare presents significant challenges and opportunities, and the field of HFE plays a crucial role in addressing and advancing this frontier. HFE principles are essential in the design and development of neurotechnologies aimed at assessing brain function.

Neuroergonomics enables capturing and facilities capturing the brain function information in unrestricted real-world settings, in order to utilize for translation in personalized health approaches. As the healthcare transition shifts increasing number of healthcare tasks and activities from clinics to home environments, from healthcare professionals to family caregivers, there's increasing need for HFE.

6.7. Ramifications of personalized healthcare for HFE in developing countries

Implementation of personalized healthcare that facilitates the adoption of medical treatment to specific human characteristics such as genetics, lifestyle, and environmental factors can have significant implications for HFE professionals in developing countries (Godman et al. 2013; Yager, Domingo, and Gerdes 2008). First, appropriate systems and processes will need to be developed to ensure the accurate and secure collection of patient records, genetic information, and lifestyle data in developing countries where healthcare infrastructure, such as healthcare laboratory facilities and information technology systems, may be inadequate (Ariani, Koesoema, and Soegijoko 2017; Adeniji, Dulal, and Martin 2021). Second, due to literacy levels, language barriers, and poor infrastructure in developing countries, the accessibility of advanced technologies, such as genetic sequencing, wearable devices, and sophisticated health monitoring systems, can be challenging (Ahmed 2007; Adebamowo et al. 2018). Third, cultural beliefs and practices in developing countries must be followed to ensure acceptance and effectiveness of personalized healthcare systems and interventions (Alam et al. 2020; Bhutta et al. 2005). Fourth, to prevent potential healthcare inequalities and assure equitable access to personalized healthcare services, the issues of care affordability, geographic accessibility, and healthcare literacy must be considered (World Health Organization & World Bank Group 2018). Fifth, since the adoption of personalized healthcare in developing countries, can require the development of new competencies of healthcare personnel (e.g. interpretation of genetic data, use of advanced technology, and patient counseling on personalized treatment options), training programs and tools to support the healthcare workforce development are needed (Nagy et al. 2020). Finally, there are several potential ethical considerations, such as patient privacy, consent, and the responsible use of genetic information; appropriate guidelines should be developed to guide the solution to the above challenges of personalized healthcare in developing countries (Wright et al. 2013).

6.8. Future prospects

Personalized Health area is currently experiencing a period of rapid improvements and development of the new capabilities resulting from applications of big data, artificial intelligence, and advances in general medical knowledge. This enables new AI technologies to diagnose illnesses and support humans living quality, healthy lives. The system-wide improvements should be used to support healthcare personnel and patients optimally. HFE practitioners, who traditionally focused on health, safety, and productivity, will need to refocus on the real-world translations with a user-centered design approach to enable a user-oriented integration of contemporary technological advances into the health care domain. One can envision multiple phases of developments to address the Future of

Personalized Health challenge. First, a large number of studies will be needed to establish the relationship of brain activity as measured with mobile neuroimaging technologies to diverse mental tasks and behavior. As most studies to date have been done in lab settings with artificial tasks due to limitations of traditional neuroimaging, a whole new generation of studies are needed to explore and map brain function in each type and category of unrestricted diverse real-world tasks and their relationship with behavior using sensors that have limited spatiotemporal coverage.

This has already started but needs community-wide effort to truly explore the extremely large variety of everyday tasks. As large datasets are being accumulated, new generations of machine learning and AI methods can be applied to capture information that wasn't available before. For example, in a recent study, published in the journal of Lancet Digital Health, authors used low-cost wearable sensors to capture real-time influenza prediction with heart rate and sleep tracking information, but using data with 200k people (Radin et al. 2020). Another example is the use of a large neuroimaging dataset and deep learning to provide diagnosis for a difficult to diagnose condition, dystonia (Valeriani and Simonyan 2020).

The second phase is the in-situ assessment of human experience during interactions with tools/technologies and other humans. This is the use of neuroscience and neuroimaging to inform the human-machine and human-human interaction understanding in discrete but natural task/scenarios. Such studies could also explore user experience, product design, and service evaluation from an operator/consumer perspective. Using strategically selected brain regions and targeting composite processes such workload, and vigilance, actionable information related to new products, user interface design, as well as cognitive and affective states related to brain health could be captured. This phase has also started with operator monitoring and passive brain-computer interfacing (BCI) studies which demonstrate the potential even with online, near-real-time applications (Ayaz et al. 2013; Gateau, Ayaz, and Dehais 2018). The third phase is the development and wide deployment of BCI's mental states that could be decoded from the measured brain signals online to translate into commands, or communication signals. Use of such direct brain-based control could help not only severely disabled patients, but also healthy individuals to augment typical ways we engage with our world and technological systems around us. Active BCIs have been researched for several decades and their types, categories, and performance are expanding (non-invasive, minimally-invasive, to invasive sensors) that can capture intention in real-time to continuously control automation (e.g. an amputee using a robot arm to drink directly from brain).

The ultimate final phase is the development of full bi-directional brain interfaces: Utilizing direct brain-based communication with our environment, automation technologies, and other humans *via* the use of neuroimaging (for output from the brain) and use of neurostimulation (for input to the brain). This stage requires innate understanding of brain regions involved in targeting mental tasks, as well as high-density recording of the activity with wearable sensors along with practical high-fidelity and high-spatial resolution stimulation. Together, these efforts will usher the dawn of a new age where brain function is easily measured for clinical assessment and everyday work tasks. The next generation tools and approaches are expected to enable diagnosis, treatment, and even prognosis of diverse neurological and psychiatric disorders.

7. Grand challenge 7: life, technology and the metaverse

7.1. Introduction to the life, technology and the metaverse

People's lives have been transformed by the widespread use of computers, mobile phones, and wearable technology in everyday lives, creating a vast interconnected network providing access to high volumes of information, increased contact between groups of people (e.g. through social media and websites), and incorporating a network-of-things (e.g. smart appliances, smart home assistants) that provide increased access to information and capabilities. Moving forward this trend will be accelerated with augmented reality devices melding online and real-world experiences and virtual reality devices providing immersion in virtual worlds known as the metaverse (Mystakidis 2022; Weinberger 2022). Coupled with the increased tendency for remote work and the ubiquitous nature of these technologies, the line between work and leisure has become blurred, as has the line between direct experiences and virtual ones. These changes provide many new opportunities for information exchange, personal interaction, learning and gaining new experiences, and new work opportunities. However, they also come with a number of profound changes to everyday life and challenges that need to be more fully understood and addressed.

7.2. Misinformation in the information age

Misinformation has become a new plague on modern society. Fostered by the advent of modern communication systems (e.g. radio, television, cell phones, and networked computer systems), as well as more recent advances in social media, the ability for inaccurate information to spread as rapidly (or more rapidly) and widely, accurate information has created a new challenge that undermines people's ability to make informed decisions. While misinformation has always been a problem, the combination and synergies of these new technologies, combined in many cases with automated network propagation (Bolsover and Howard 2017), has greatly exacerbated its reach and negative effects.

Unless the problem of widespread misinformation is addressed, society's ability to deal effectively with challenges such as climate change, pandemics, and global inequities such as poverty, terrorism and warfare, will be severely limited. The lack of a common understanding of relevant facts directly underlies the widening gap in opinion polarization that threatens democratic societies (Del Vicario et al. 2016).

Both casual misinformation and deliberate information attacks pose a significant threat to effective human decision-making and capitalize on human cognitive characteristics and weaknesses that make it difficult to overcome. Endsley (2018) provides a framework for understanding misinformation and information attack that considers its sources, features, avenues, mechanisms, and the challenges it presents for human decision making.

(1) **Sources:** Deliberate information attacks (disinformation) are being perpetrated for economic gain (by individuals as well as corporations and industrial groups) (Allcott and Gentzkow 2017; Chen, Conroy, and Rubin 2015; Hoggan 2009; Smith et al. 2011); political gain within countries (Lewandowsky et al. 2012; Ratkiewicz et al. 2011); and as a component of warfare or geopolitical maneuvering between countries (Office of the Director of National Intelligence 2017; Schaefer et al. 2016).

(2) **Features**: Disinformation surrounding events is often rapid, repeated, and high volume across multiple channels, and may employ methods such as cherry picking, inundating correct information in an avalanche of noise and conflicting stories, or simply consistently repeating false information (O'Connor and Weatherall 2018; Paul and Matthews 2016).

(3) **Avenues:** A significant amount of misinformation travels through both legitimate and phony news sites, including print, online, and broadcast news, through social media (Allcott and Gentzkow 2017), and by individuals sharing misinformation with others in their circle (Barthel, Mitchell, and Holcomb 2016; Vosoughi, Roy, and Aral 2018), with stories originating from unreliable sources often echoed by more reliable sources unwittingly or through hasty reporting (Paul and Matthews 2016). Automated network propagation, in which automated bots spread disinformation and propaganda has contributed significantly to its spread (Bolsover and Howard 2017; Schaefer et al. 2016), and new avenues, such as 'deep fake' videos are only likely to increase the problem in future.

(4) **Mechanisms:** Disinformation takes advantage of known human decision biases, such as anchoring, confirmation bias, and cognitive dissonance, and often plays on emotions and social cognition (e.g. group norms and belonging) to be successful and hard to combat. As shown in Figure 5, a negative cycle exists that undermines people's willingness or ability to attend to relevant information, accurately assess information reliability or veracity, combine or weigh information from various sources, and project the effect of future actions (Endsley and Jones 2001; Jones and Endsley 2000). Without either the ability to filter accurate versus inaccurate information, or to project the outcome of various decision options (e.g. getting vaccinated, supporting a specific policy, or voting in an election), public decision-making and democracy are effectively undermined by a broken feedback cycle.

(5) **Challenges:** Additional challenges exist for combating information attacks, including: peoples' poor understanding of information reliability (Allcott and Gentzkow 2017; Cook, Ecker, and Lewandowsky 2015; Gallup-Knight Foundation 2018); social reinforcement effects in which people's attitudes and beliefs are significantly and subconsciously influenced by their cultural and social group (Cohen, 2003; Wlezien and Miller 1997); an often strong tendency to resist information that conflicts with established false beliefs (Allcott and Gentzkow 2017; Lewandowsky et al. 2012); the backfire effect in which those who are resistant to corrections of misinformation can actually increase their belief in the false information (Nyhan and Reifler 2010); and poor feedback loops in which correct information can be both slow to arrive and buried in a noisy information environment that prevents people from correcting false mental models.

7.3. Personal data and data analytics

Smartphones, wearable sensors and social networks provide a new approach to data collection, and with them the opportunity to provide new insights into human life (Sharples and Houghton 2020). A review of internet-of-things (IoT) technologies suggests there are challenges to integrating streaming data from the multitude of machines and products capable of transmitting data. For example, home appliances, thermostats, security devices and other technologies can provide detailed information that could be used for many applications.

Intelligent monitoring based on wearable sensors and social networking data is popular. Health, education, training and safety have significantly increased in terms of emphasis in Google books from 1985–2010, with a growing emphasis on wellness monitoring applications. Wellness applications take into consideration a person's lifestyle leading to improved physical, mental and social wellbeing. Wearable technologies create a large amount of unstructured data. Existing approaches for collecting and managing this resource are limited in their ability to deal with the large volumes of streaming data generated, particularly with respect to feeding that data into the broader system (Ali et al. 2021), dealing with data that is often noisy and of mixed quality, and not well understood uses of the data. Utilization of this information remains limited. Providing ways to easily identify and track objects within the system, and applying the information to actual user needs is a challenge.

Very large data sets can be captured by ubiquitous technologies and sensors (e.g. cell phones, social media, search engines, fitness trackers, home based sensors) which can provide unique insights into the movements, activities and interests of people. However, we live in an age where the amount and complexity of data available far surpasses our ability to understand or utilize it in decision-making (Marriott et al. 2018). There is a digital divide in value creation between big data and data analytics that is emerging with respect to utilization of big data (Gravili et al. 2018).

7.4. Privacy and universal surveillance

As satellites, computers, internet, smartphones and social media have modified and reconfigured our societies, the ethical principles and privacy of individuals are at risk. Although modern technology has increased the ability of individuals to interact with and understand our physical and social environment, if allowed to go unchecked, the individual will be severely impacted by being surveilled, tracked, and exposed to information and misinformation targeted to their beliefs. On-line surveillance constrains both online speech and offline speech (Marder et al. 2016). Tools that were once the sole province of national armed forces have been democratized and made available to a wide range of unregulated actors including corporate entities, non-state actors, and criminals (Chen, Beaudoin, and Hong 2017). Trust in institutions, governments, and individuals has been decreasing in recent years (Perry 2021), and widespread surveillance can only reinforce such a trend.

Surveillance is not new: People have always had other people spying on their activities, from nosy neighbors, to governments, to foreign entities. Significant surveillance improvements introduced in the last century include: (a) improved sensor quality; (b) more remote sensors; (c) sensors embedded into every-day objects with users not fully understanding their capabilities and actions; and (d) automation that can augment or replace human cognition and pattern-recognition ability. This has allowed almost invisible surveillance at high resolutions with the ability for one human surveillant to monitor many subjects. Devices such as high-resolution satellites and drones, along with urban TV cameras equipped with AI facial recognition, can track people's mobile phones and movements, so that they, generally unknowingly, give away large amounts of data about their actions and beliefs.

Although surveillance has legitimate uses (e.g. terrorist activities, addictive drug manufacture/distribution, offensive military/missile attacks), the situation has passed beyond these potentially legitimate uses of surveillance (e.g. see Stanger (2020) with respect to surveillance of the general population, and Moore, Upchurch, and Whittaker (2018) for the workforce). There are at least three technical contributors to universal surveillance that need to be addressed by the HFE community to truly give individuals choice regarding the level of surveillance they wish to tolerate.

(1) **Optical-based surveillance**: Visual technology has advanced in two main directions: The ability to collect large quantities of visual data and the ability to search and understand the implications of this data. Cameras are built into many devices used every day by the general population, (e.g. mobile phones, consumer drones, CCTV cameras (Michael and Michael 2013)) and specialized wearable cameras such as police 'bodycams'. Much of this information is recorded and stored so that it can be used both rapidly (e.g. crowd monitoring) and retroactively (e.g. reviewing crime scenes that were not being actively surveilled when the crime was committed). As Michael and Michael (2013) point out, facial recognition software based on artificial intelligence can identify individual citizens with some degree of accuracy, which will only improve over time (Ansari and Singh 2021).
(2) **Software-based surveillance**: The size and growth of participation in social media has been spectacular. In 2021 the estimated worldwide usage was about 4.48 billion, 56.8% of the world's population. Many users regularly get their news from social media (Walker & Matsa, 2021), making it a prime means of surveillance. Even devices such as Kindle readers may collect personal data on users and their preferences (Wicker and Ghosh 2020).
(3) **Tracking of personal devices**: Many devices equipped with GPS capabilities, such as mobile phones and watches, referenced above for visual surveillance (Michael and Michael 2013), can also include their own tracking systems, adding another level of surveillance often unnoticed or ignored by users (Soper 2012). Most mobile telephones generate at least rudimentary tracking data, such as the closest cell tower. While there are ways for individuals to minimize their surveillance, these are usually not the default settings on mobile phones.

7.5. Technology and the new reality

Mobile information devices have become widely distributed in modern society, providing instant voice, text, and video communications along with access to information in various formats. Further new, more immersive, forms of information delivery are becoming common. This includes virtual reality (VR) which is widely used for gaming and training, augmented reality (AR) which superimposes virtual imagery or text on the natural world, either on mobile hand-held devices, glasses or goggles, and mixed reality (XR) that combines VR and AR. These technologies can provide significant advantages in terms of their ability to provide easy access to vast reservoirs of information, any-place any-time access to education, training, and entertainment, and a remote means of controlling technologies (e.g. thermostats and cameras), as well as communications across widely dispersed individuals. As technology has become ubiquitous in everyday life, however, new challenges become prevalent.

Technology can significantly shift attention away from the natural world towards the virtual with ill effects for human performance. For example, distracted driving has been shown to be significantly increased by the use of cell phones in automobiles by creating an 'inattention blindness' to the driving task that corresponds to the attention demands of the competing activity (Strayer and Cooper 2015). Reduced situation awareness occurs from reductions in both visual scanning and mental projections of the driving situation (Ma and Kaber 2005). In-vehicle entertainment systems and GPS navigational devices similarly can shift attention away from the driving task towards these other competing, and highly compelling, information devices. This problem does not just exist in driving, but can occur in other venues. For example, the ill-effects of cell phone usage on walking safety have been shown in a number of populations including children, college students, and older adults (Stavrinos, Byington, and Schwebel 2009, 2011; Weksler and Weksler 2012).

As the delivery of information shifts from displays or cell phones to AR, the opportunity for virtual information to intrude on performance in the natural world can actually become greater. The natural world information is not processed in parallel with virtual world information, even when it is superimposed visually (McCann et al. 1993). When using AR devices, peoples' attention can get captured by the virtual information, to the detriment of their attention to information the natural world. For example, two men were killed falling off of a cliff while absorbed in a game of Pokémon Go that involved capturing AR characters that were distributed in different geographical locations (Hernandez 2016).

The impact of technology need not be direct, but can also occur in indirect ways. Reduced performance on tasks has been shown to occur even due to notifications and ringing on cell phones, as it redirects attention towards socially-related thoughts, even when people do not interact with the phone (Stothart, Mitchum, and Yehnert 2015; Thornton et al. 2014). Ward et al. (2017) showed that students who had cell phones present on the table (but did not use or interact with them) performed worse on tests than when they were told to put them out of view during the test. Just the presence of the technology was a sufficient distractor to effect performance, acting to reduce cognitive capacity.

7.6. Importance to HFE discipline and profession

7.6.1. Misinformation in the information age

Although the HFE profession has traditionally been focused on improving the relationship between people and technology in workplaces, the expansion of information technologies into the personal sphere creates the need for a much wider focus to address the ways that technology change the human experience and the need for solutions to new classes of problems. The HFE profession can significantly contribute to addressing the challenge of misinformation due to its historical focus on improving people's ability to perceive and process complex information in other contexts, with within and outside of workplaces, including *via* computer displays on which people are increasingly reliant for information.

7.6.2. Personal data and data analytics

HFE professionals can leverage developments in the field of data mining and data analytics through nearly all research projects. An understanding of the impact on the research community can be gleaned through the use of bibliometric analysis (Duffy and Duffy 2020; Duffy 2021). A trend diagram from Scopus, Figure 6, suggests there is an increasing

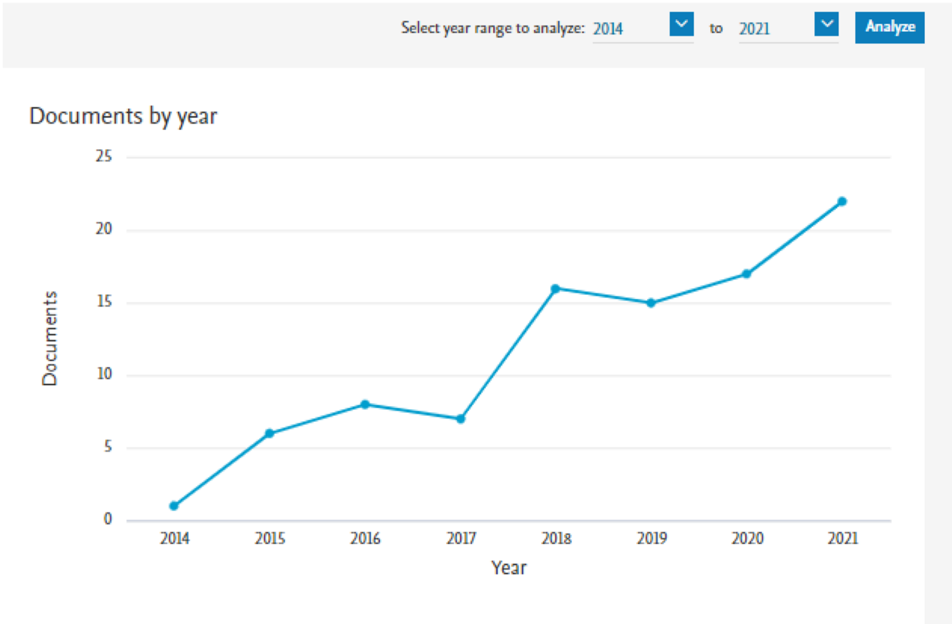

Figure 6. A trend diagram from Scopus (2022) database in search for 'data analytics' and 'ergonomics' or 'human factors' suggests there is an increasing opportunity for ergonomists and human factors specialists to participate in this growing area.

opportunity for ergonomists and human factors specialists to participate in the growing area of data analytics, with wellness and health monitoring indicated as related and emerging areas. Although automation and assistive technologies are becoming more prevalent in IoT technologies, the usability of this information remains a challenge (Brudy et al. 2019; Craggs and Rashid 2017; Parkin et al. 2019; Thomas et al. 2016). HFE considerations are generally underrepresented in this research stream resulting in an important research and application gap (Goundar, Kumar, and Ali 2022; Neumann et al. 2021; Parkin et al. 2019). A focus on usability of wearable technologies; fit, comfort and safety of wearable technologies; and better integration of data into meaningful information, all are well within the realm of HFE contribution.

7.6.3. Privacy and universal surveillance

Better methods for informing people of the types of surveillance they are undergoing are needed.

Currently information on data sharing and tracking is generally deeply imbedded on mobile devices and in complex user agreements. Research is needed to find ways of allowing people to better understand the uses and implications of data sharing and tracking across applications.

7.6.4. Technology and the new reality

The ubiquitous use of information technologies in everyday life presents new challenges for the human factor's profession. Given their use by populations of varying capabilities in a wide variety of environments and situations, how can these technologies be designed to improve people's ability to multi-task, or to discourage them from multi-tasking if that is not possible? A new challenge exists for human factors researchers to better understand the impact of these new technologies on human performance and safety, and how to improve their design to best optimize human outcomes.

7.7. HF/E strategy to address this challenge

7.7.1. Misinformation in the information age

Endsley (2018) outlines a number of ways that the HFE profession can play a significant role in addressing the challenge of misinformation and information attack to help people better determine the factuality of information, including creating improved methods for information presentation in verbal communications as well as on websites and in social media, and supporting the assessment of information confidence. Methods for combating decision biases, including the combined effects of anchoring, confirmation bias, and representative bias are needed. HFE research needs to consider the emotional aspects of disinformation to find ways to reduce defensive mindsets and to increase objective information processing over directed reasoning. The strong role of social groups on opinion formation must also be considered, pointing to the need for research on reducing group think and changing opinions in group settings.

Sociotechnical approaches for addressing the effects of automated bots, false news, and misinformation across social media are needed. Although modern technologies have promised to move the world into the information age, the result has been greatly diminished by a plethora of misinformation and disinformation. Effectively dealing with this grand challenge very much requires an understanding of the interactions between the human, social, and technical components of the system, and the concentrated efforts of the HFE profession.

7.7.2. Personal data and data analytics

HFE needs to be applied to addressing the digital divide, overcoming current obstacles in order to support the decision-making processes of potential users of big data. HFE can have a significant influence on the best ways to optimize human values *via* the design, use and integration of big data so as to achieve the desired benefits of this resource. Modern hardware and software development has enabled natural user interfaces and virtual immersive and augmented environments in support of the use of the big data with integrated supporting data analytics (Bachmann, Weichert, and Rinkenauer 2018). There is a great deal of expertise in the HFE field that can contribute to addressing current challenges related to human-technology usability and systems-related integrations of big data.

Challenges lie in the scale and complexity of health, wellness and health monitoring. Human–computer interaction (HCI) principles are being applied to support research recognizing complementary interactions within personal data (Blandford 2019). HFE specialists can assist to fit individual and contexts to wearable technologies. With support from HFE, there is a greater likelihood that frameworks and other performance measures can be developed to better support personal monitoring and data analytics, allowing them to become useful devices for personal health and fitness.

7.7.3. Privacy and universal surveillance

The potential for widespread surveillance to interfere with personal privacy is a problem caused by technology extending the capabilities of humans, and so should be amenable to HFE analysis and design. So far, HFE has had minor impact on surveillance, largely confined to changing the technology and interface to improve system performance. HFE needs to move well beyond such studies and into the arena of ethics of surveillance to provide a more balanced picture of the human-technology interactions involved.

One area in which HFE has relevant expertise and credibility is in the measurement of trust. Trust has a long history of measurement and analysis in the public sphere (Perry 2021), while human factors expertise has typically been applied to trust in automation, e.g. Jian, Bisantz, and Drury (2000). In addition to considerations of trust, HFE research is needed to help protect the population from unwanted, and often unseen, surveillance. The HFE profession needs to help make the details of surveillance more explicit and make it easier for individuals to opt out. This involves more transparency and better interface design, both standard HFE design techniques. For example, it would be best to make the most beneficial choice for users be the default in a menu, extending the default options idea of Thaler and Sunstein (2021) to online choices. Transparency applies equally to removal of hidden surveillance (i.e. spying). Note that the concept of transparency as an antidote to surveillance has recently come in for criticism in a broader sociological context (Viola and Laidler 2022). Research is also needed on visual, software-based, and personal tracking threats to privacy, as well as to uses of AI in facial recognition. Further, the HFE profession needs to strengthen and expand its efforts to translate this research into practice *via* government agencies and legislative actions where required.

7.7.4. Technology and the new reality

Research on the use of AR and VR devices has been underway in the HFE community for some time (Burdea 1999; Evans 2018; Stanney 1995; Sharples et al. 2007; Thomas and Stuart 1992; Wann and Mon-Williams 1996). The current work needs to be extended to the broader application of AR and VR in many real-world applications (e.g. driving, healthcare, education) where it is being applied. Attention to the effects of mobile technologies, their use and ubiquity in every-day life, as well as in operational conditions, also needs further research attention. It is important that this research move out of the limits of laboratory situations into contextually representative real-world applications as ecological validity will be crucial for determining relevant factors and interventions for promoting human performance.

7.8. Ramifications for HFE in developing countries

Given the ubiquity of advanced technologies across the globe, including in developing countries, the challenges described are universal. The use of cell phones is currently estimated at 85% of the world's population, for example, and rising (Statista 2023). Viral sharing of misinformation has been found to be a problem worldwide (Arechar et al. 2023). And issues of privacy and surveillance are universal. Further, as the world becomes more interconnected through widespread use of personal technologies (e.g. teleconferencing, connected messaging applications, and social media), the opportunity for these problems to magnify increases.

7.9. Future prospects

The HFE profession has a grand new challenge in better understanding how these technologies will impact human attention and behavior and helping to design interventions to improve their safety. Moving forward, significant investments are being made in the development of virtual worlds, connected over the internet, that are loosely described as the metaverse. These virtual worlds provide increasingly realistic renditions that extend current gaming or fantasy worlds into even more extensive applications allowing entirely new paradigms for social interaction, virtual meetings, and virtual experiences. In such worlds where reality is artificial, distinguishing fact from fiction becomes almost impossible, and the opportunities for monitoring of human behavior and interactions is absolute, making privacy illusory at best.

The impact of the newly developing metaverse is not fully known. While new opportunities may abound, current research shows that technology-mediated interactions tend to exacerbate people's willingness to mistreat others (e.g. trolls and cyber-bullies) (Hamm et al. 2015), and can increase depression (Lin et al. 2016), which could become worse in terms of their impact in more fully immersive worlds. Further, the significant attentional draw of compelling virtual worlds may have serious consequences for the neglect of relationships, jobs, families, and physical well-being in the real one.

8. Conclusions

8.1. Implications of HFE grand challenges for research

Table 6 presents the key research thrust areas for each of the identified HFE grand challenges. The main research questions identified under the grand challenge of *Evolution In Societal Thinking* center around the need for universal adoption and application of systems thinking for analyzing, preventing, and managing longstanding and complex global risks problems. The grand challenge of *The Future Of Human Work in Industry 5.0* discusses the implications of Industry 5.0 with a particular interest in the issues of autonomy, transparent and trustworthy artificial intelligence, and human-centered design of digital twin integration and extended reality. The grand challenge of *Climate Change And Sustainability* points out the need for research on resource scarcity, combating overexploitation of resources, a better understanding of cross-system complexity, ecological resilience and adaptation to climate change, and developing ethical principles to secure a sustainable future. The grand challenge of the *Future Of Personalized Health Focuses* on the development of phenotypes based on understanding causal pathways for musculoskeletal disorders, optimizing health technology for the older adults, managing ethics and privacy in the era of big data, reducing risks of injury from healthcare settings and providers, and bringing the brain into the loop of healthcare. Finally, meeting the grand challenge of *Life, Technology, And The Metaverse* necessitates research on managing misinformation and preventing cyber-attacks, improving human-technology usability, including the effects of augmented and virtual reality on human performance, understanding the electronic surveillance policies and privacy risks, helping users in understanding and taking advantage of personal health monitoring technology, and enabling integration of big data and the internet of things.

Table 6. Key research thrust areas for each of the six HFE grand challenges.

Grand HFE Challenge: Evolution in Societal Thinking

- Developing a unified theory to address complex global risks
- Utilizing systems thinking and sociotechnical systems theory for improved global risk management strategies
- Employing systems thinking methods to tackle complex issues, as identified by the World Economic Forum
- Identifying evidence on the effectiveness of systems thinking in solving longstanding complex challenges

Grand HFE Challenge: Future of Human Work in Industry 5.0

- Promoting Human-Centered, Transparent AI and Autonomy in Industry 5.0
- Enhancing Accessibility to Extended Reality Technologies in Industry 5.0
- Fostering Trustworthy AI and Autonomy in Industry 5.
- Addressing Misinformation in Industry 5.0

Grand HFE Challenge: Climate Change and Sustainability

- Assuring dignified work, tasks, and technologies
- Supporting sustainable practices within organizations for better environmental, social, and corporate governance
- Promoting life-cycle analysis, circularity, and sustainable supply chains at the interorganizational level
- Developing and validating tools for social and environmental systems sustainability
- Adapting HFE educational curricula to enhance systems' sustainability and resilience
- Developing ethics and values for HFE to forge a sustainable future

Grand HFE Challenge: Future of Education and Training

- Exploring the economics of student behaviors across all educational levels and special populations
- Leveraging diverse media for designing effective educational processes and instruction for both in-person and remote learning
- Equipping educators with tools for a deep understanding of student needs and personalized teaching strategies
- Implementing human-centered design for inclusive education, focusing on individuals with disabilities and older adults

Grand HFE Challenge: Future of Personalized Health

- Developing phenotypes through causal pathways analysis for musculoskeletal disorders
- Optimizing health technology usage among older adults
- Addressing ethical and privacy concerns in the era of extensive health data
- Minimizing healthcare-related injury risks
- Integrating brain function considerations into healthcare solutions

Grand HFE Challenge: Life, Technology and the Metaverse

- Enhancing human-technology interaction and system integrations for big data and the Internet of Things
- Creating methods to assist users with personal health monitoring devices
- Developing strategies to combat misinformation and information attacks
- Improving public awareness of electronic surveillance and privacy risks
- Formulating strategies to mitigate negative impacts and maximize the benefits of information technologies, including augmented and virtual reality

8.2. The HFE knowledge and skills development requirements to meet the grand HFE challenges

To date, HFE practice has been mainly based on 20th-century knowledge. The development of new knowledge, identification, and adoption of recently developed 21st-century models, theories, and strategies in the related fields of science, engineering, and medicine should help address the identified grand HFE challenges. Table 7 provides several examples of the new HFE knowledge and skills that will need to be developed or enhanced to meet the discussed grand HFE challenges. The above points out the need to significantly expand the current knowledge content of the HFE domain. Such a need is primarily driven by the rapid development of intelligent technologies, the evolving global economy, the sustainability of life on Earth, and a multitude of emerging socio-economic trends that will likely transform and shape modern societies. However, we also realize that the applications principles of

Table 7. The HFE knowledge and skills development requirements to meet the grand HFE challenges.

Grand HFE challenge/examples of HFE knowledge requirements: theory and practice
Evolution in Societal Thinking
○ Mastery of systems thinking and the dynamics of complex systems ○ Understanding of artificial intelligence (AI) and machine learning basics ○ Application of HFE tools and methods for complex system analysis and design, prompted by technological advancements ○ Human-Centered Design (HCD) principles for AI, focusing on ethics and human-AI collaboration ○ HCD approaches for autonomous vehicles, considering passenger perceptions and concerns. ○ Strategies for improving the lives of older adults through technology ○ Design principles for technologies that promote independent thinking and cognitive independence ○ HCD for social and service robotics ○ Insights into human experiences in the cyber and space age
Future of Human Work in Industry 5.0
○ Basics of data analytics ○ Understanding of human and machine autonomy ○ Impact of AI on workforce dynamics, including social and psychological aspects ○ Integration of human-digital twin systems ○ Industry 4.0 and 5.0: theory and practice ○ Concepts of informal work and the casualization of labor ○ AI and sociotechnical cyber systems ○ AI skill requirements and worker retraining
Climate Change and Sustainability
○ Climate and sustainability fundamentals ○ 'Green' HFE and ergo-ecology principles ○ Carbon neutralization strategies ○ Human motivation and attitudes towards climate change ○ Human-centered climate change responses ○ HCD for global resource conservation
Future of Education and Training
○ Technological and computer science literacy ○ Optimizing digital and remote education ○ Developing educational support systems tailored to individual needs ○ HCD of explainable AI for personalized training and assistance ○ Strategies to advance the HFE education in developing countries ○ HCD for space exploration and living ○ Future of personalized health and public health basics ○ HFE strategies for pandemic prevention and mitigation ○ Human-centered public health principles ○ HCD for personalized health information systems design ○ Brain-computer interface applications for neurological conditions ○ HCD for mental health improvement ○ HCD for cognitive assistance tools for the disabled and older populations ○ Neuroergonomics: theory and practice
Life, Technology and the Metaverse
○ Fundamentals of network science, social media and metaverse ○ HCD in extended realities and synthetic environments ○ Virtual world ethics and safety ○ Strategies for managing post-truth and surveillance societies ○ Social media analysis: misinformation, decision-making irrationality ○ Misinformation combating methods ○ Online opinion polarization theories ○ Cognitive freedom, privacy, and societal risk principles ○ HCD for data misuse correction, rebuilding public trust, and societal unification.

human-centered design and HFE knowledge, in general, have not yet been universally adopted into many contemporary systems and rapidly evolving technologies (Karwowski 2005; Karwowski et al. 2014; Karwowski and Zhang 2021; Thatcher, Nayak, and Waterson

2020). Furthermore, we acknowledge that the identified HFE challenges can only be fully addressed by applying the non-HF/E core expertise, including the knowledge of engineering, technology, economics, and management, as well as government regulations and public policy solutions. Nevertheless, we hope this paper will contribute to the current discussion about the future of HFE stimulate much-needed reflections on HFE challenges, and facilitate developments in HFE theory and practice for the benefit of humankind.

8.3. HFE grand challenges and professional practice

In general, the discussed grand challenges for HFE have several implications for the professional practice at the global scale, including (1) considerations of rapid advancements in technology, (2) the impact of evolving work environments, (3) the effects of an aging population on accessibility, (4) the consequences of globalization and cultural diversity, (5) the influences of ethical and privacy concerns, and (6) the need for interdisciplinary collaboration. First, the fast advancements in computing technologies, AI, quantum computing, virtual and extended reality, and wearable devices present both opportunities and challenges for HFE practitioners who will need to develop a deeper level of understanding of the effects of such technologies on the evolving quality of human-system interactions and their impact on human and system performance (Agah 2000; Bernsen 2001; Schuetz et al. 2020). Second, as the nature of human work is changing with the adoption of remote work, the onset of the gig economy, and pervasive automation, HFE practitioners will need to adapt the relevant methods and approaches to address the specific challenges associated with quickly evolving work environments (Howcroft and Taylor 2023; Prassl 2018; Tyagi and Abraham 2020; West, 2018). Third, since the global population rapidly ages, consumer products, services, and environments must be designed to ensure their accessibility by all users, including accommodations for older adults and people with alternate abilities (Cohen, 2003; WHO, 2007; WHO, 2007). Furthermore, HFE practitioners must focus on designing inclusive solutions that consider the needs and capabilities of diverse user populations (Clarkson et al. 2013; Steinfeld and Maisel 2012; WHO, 2007). Fourth, as new computational and communication technologies are being rapidly incorporated into the everyday lives of billions of users worldwide, there are growing concerns about personal privacy, data security, and ethical use of technologies (Atlam and Wills 2020; Brey 2007). HFE practitioners will also need to focus on applying ethical guidelines to design systems that would protect user privacy and autonomy (Dhirani et al. 2023; Santosh et al. 2021). Fifth, since the HFE discipline is essentially interdisciplinary, addressing the stated HFE grand challenges will require extensive collaboration with professionals from other disciplines, such as psychology, engineering, design, systems science, and computer science (Boy 2017; Ozmen Garibay et al. 2023). Finally, effective communication and collaboration across other related disciplines will be needed to address complex issues related to the six HFE grand challenges discussed above.

9. Study limitations

We would like to stress out that our paper does not claim to represent the views of the global HFE community as we did not have co-authors from the major developing countries. Also, while the authors collectively represented a broad range of knowledge in the HFE and related domains, our group did not include a psychosocial scientist. The above could result in cultural biases when developing and discussing the proposed Grand HFE Challenges. Second, an important challenge of changing the demographics of the global population in terms of age, race, culture, and ethnicity and its potential impact on the future of work, healthcare, transportation, and living environment policies have not been explicitly discussed. Third, we have not specifically addressed an important human factor, individual differences, that play a critical role in applying HFE knowledge in practice. Fourth, we offered a very limited discussion of the psychosocial issues, including the effects of social isolation and loneliness during the COVID-19 pandemic and the potential benefits of technology that could facilitate the opportunity for people to connect virtually. Fifth, concerning the Grand Challenge of the Future of Education and Training, we did not address the ramifications for the developing countries that might be unable to afford to implement the modern technologies we discussed. Furthermore, we did not consult educational psychologists or experts on the education related matters. Sixth, we did not extensively discuss the implications of HFE's grand challenges for professional practice. This is an important area that requires allocating significant publication space to address. It is noted that some recent studies provide examples the real-world applications, including case studies or successful HFE interventions, that can help to bridge theory and practice and make the discussed grand challenges more tangible for practitioners (Dewantari and Herlina 2022; Luo et al. 2023; Levine et al. 2024; Privitera 2020; Read et al. 2024; Wooldridge, Carman, and Xie 2022). Future studies should focus on and explore the implications of the above limitations and shortcomings.

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The authors report that there are no competing interests to declare.

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