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To Safety and Beyond!
A Scoping Review of Human Factors Enriching the Design of Human-Robot Collaboration

Jasper Vermeulen[1,2], Glenda Caldwell[1,2], Müge Belek Fialho Teixeira[1,2]
Alan Burden[1,2], Matthias Guertler[1,3]

[1] Australian Cobotics Centre, Australia
[2] Queensland University of Technology, School of Architecture and Built Environment, Faculty of Engineering, Brisbane, Australia
[3] University of Technology Sydney, Australia
jasper.vermeulen@qut.edu.au

Abstract. This scoping review explores human factors that enrich the design of Human-Robot Collaboration (HRC) beyond the traditional focus on ergonomics and safety. As Industry 5.0 shifts towards a human-centric perspective, understanding the multifaceted interactions within socio-technical systems becomes crucial. The review investigates diverse fields, including design, psychology, and engineering, to identify human factors influencing the successful integration of Collaborative Robotics. The research findings confirm the need and potentiality of using the holistic lens of human factors to illuminate human-centric needs in HRC designs. Moving beyond quantitative measures, the study advocates for qualitative insights to inform the design of HRC and enhance worker conditions through individualised and contextualised experiences of collaborating with cobots. The findings contribute to advancing the understanding of HRC's complexity and underscore the significance of user-driven perspectives in future research and design efforts.

Keywords: Human factors, Human-Robot Collaboration, Designing Socio-Technical Systems, Collaborative Robotics, Industry 5.0

1 Introduction

Traditionally, robots have been part of technological innovation that has mainly dominated Science Fiction literature, often working at the demise of humanity. In practicality, however, robots are an enabling technology designed in ways that are supportive of human efforts. In industry, robots can be seen as an enabling technology for standardisation and mass production [1]. Consequently, manufacturing and other industries have seen the rise and use of industrial robots. Industrial robots are fenced robots that can be programmed or controlled from a distance to produce standardised results [1].

However, the European Union recently coined a new era in the Industrial Revolution known as Industry 5.0 or the 5th Industrial Revolution, which moved from a techno-centric to a human-centric view [2, 3]. Effectively, this alteration means that such robots are introduced with different motives; rather than utilising robots for increased process output, robots are brought into the workplace to aid the human worker in fulfilling their job. With the emergence of Industry 5.0 (I5.0), three new pillars have been introduced that focus on customisability, sustainability and the human worker [4]. As such, these recent technological developments support the further design, use and implementation of Collaborative Robotics (Cobotics) and collaborative robots (cobots), which were introduced during the 4th Industrial Revolution [5].

The transition from (traditional) industrial robots to cobots is characterised by increased safety mechanisms allowing for the removal of space between the human and the cobot. Cobots are designed to interact closely with humans to work in conjunction towards a common goal. To allow for this close collaboration, cobots are embedded with the following safety modes: (1) safety-rated monitored stop, (2) hand-guiding operation, (3) speed and separation monitoring, and (4) power and force limiting [6]. In manufacturing, three distinct ways of working with robots have been identified: (1) sequential, (2) cooperative and (3) collaborative [7, 8]. Due to their embedded safety modes, cobots can work closely together (collaboratively) on the same task. Cobots have the potential to relieve workers of heavy and repetitive tasks while simultaneously allowing workers to use their creativity and flexibility [1]. Manufacturing is but one example where cobots can and are being employed; other areas include healthcare (robot-assisted surgery) and construction [6, 9].

Generally, in these socio-technical systems, systems consisting of humans and cobots closely collaborating, there is a potential to achieve synergy, designing a symbiotic stasis in which humans and cobots complement each other to produce greater outcomes [10, 11]. Specifically, in line with the Industry 5.0 vision, this could adhere to higher forms of customisation and support I5.0's mission of improving worker conditions through enabling technologies like Cobotics [3]. This focus on worker conditions is not novel in the context of humans interacting with robots. Therefore, it is crucial to establish the difference between Human-Robot Interaction (HRI) and Human-Robot Collaboration (HRC). Simões and colleagues (2022) provide a helpful description as they perceive HRI to consist of the actions and information exchanges between humans and robots during certain tasks. Herein, HRI focuses on the interface that enables these interactions. HRC, on the other hand, comprises a more complex evolution of HRI, focusing on the human and the robot working together in the same space on the same task [12, 13]. It is thus helpful to approach HRC from a systems perspective as it is a complex socio-technical system consisting of the human, the cobot and the environment [2, 14]. This understanding also lends itself well to the analysis through the holistic lens of human factors. The lens of human factors can offer a more comprehensive understanding which encompasses physical, cognitive, social, emotional and environmental factors [2, 14–16].

Nevertheless, the majority of literature thus far on this topic has been concerned with the core principle of safety in HRC [14, 17–19]. In particular, investigating how the (physical) ergonomics of the worker is affected by HRC [20]. Recently, other works have started to include cognitive ergonomics as well [17, 21]. Cognitive ergonomics is concerned with mental processes, as these can be seen to affect the interactions between humans and cobots [16]. In other words, cognitive ergonomics often centres around the mental or psychological state of the worker, e.g. mental strain [22]. Furthermore, the field of HRC is emergent but also interdisciplinary [23], for example, it draws on influences from fields such as Robotics, Engineering, Design and Psychology. The existing efforts into human factors of HRC centre around the concept of (physical) safety and are often explored through the lens of Robotics, Engineering and Ergonomics [14]. Recently, several efforts from the field of Psychology have started to explore cognitive ergonomics in HRC [24, 25]. While few efforts from a Design angle exist [20, 26], the existing studies primarily focus on the concept of safety in HRC. Other works that focus on the design of human factors in HRC are limited to industrial contexts [12, 22, 23, 27, 28]. Therefore, in this work, we aim to contribute to the growing body of literature by conducting a scoping review that explores a holistic approach towards human factors in HRC from a Design perspective. In other words, we aim to go beyond the lens of safety in HRC and beyond the industrial context. Furthermore, with the Industry 5.0 vision in mind, the design of HRC will increasingly centre around the human conditions of the workers engaging in HRC. Nevertheless, in existing studies on human factors in HRC, there is a predominant focus on utilising subjective (quantitative) measures to analyse human factors that affect the design of HRC. Although subjective measures such as self-reporting were frequently used in the examination of cognitive ergonomics [29, 30], it becomes clear that many studies preferred a data-driven approach rather than a human-driven approach to the research. For example, [27] introduced a cobot in an assembly task and focused on increased efficiency and improved postures. While objective measures are useful, mainly in improving a cobot for HRC applications, there is a potential to obtain subjective and richer, qualitative data that informs the design of HRC. Therefore, in order to design a socio-technical system which brings human-cobot synergy into fruition, it is required to understand the human factors that enrich this process. Consequently, the following question guided the research:

- What are the human factors that enrich the design of HRC?

To answer the research question, we conducted a scoping review according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for scoping reviews [31]. This method allowed us to use a systematic approach towards providing a global view of human factors that enrich the design of HRC. This research aims to contribute to the growing body of literature on HRC and human factors by providing a novel perspective that stresses human-centric approaches to human factors in the design of HRC. The insights of the scoping review reveal that human factors and ergonomics in HRC have been intertwined and, consequently, the field of HRC and human factors could benefit from going beyond these lenses (study of ergonomics and safety) and start to include more user-centric and contextual approaches by incorporating user experiences in HRC. Additionally, the results illustrate the complex nature of Cobotic socio-technical systems as the human factors that enrich its design appear interrelated. Therefore, future research should include empirical, qualitative inquiries that use more holistic approaches to unlock the true potential of HRC and improve worker conditions through individualised experiences of HRC.

2 Method

In this study, we selected scoping reviews as a methodology to answer the research question. Scoping reviews provide a systematic way of summarising and grouping findings from a specific field [32]. Moreover, as human factors in HRC is an emerging research area, a scoping review is deemed more suitable than a systematic review [32]. Scoping reviews are an effective literature review method for presenting a global overview of identified concepts, themes and factors [31]. Despite selecting the method of scoping reviews rather than a systematic review, we aimed to conduct our literature review in a systematic, rigorous and reproducible way. As such, we used the PRISMA extension for scoping reviews [31].

2.1 Purpose and Search Strategy

This step comprised of defining the objective of the study and crafting an appropriate search strategy. In this study, we are concerned with identifying the human factors that enrich the design of HRC. It is important to note that there are no unified or agreed-upon descriptions of what human factors and ergonomics in HRC entail [2, 17, 33]. This is further complicated as these terms are often used interchangeably and synonymously [34]. Only the recent work of Abdulazeem and Hu (2023) aimed to provide a thorough description that differentiates between the concepts of human factors and ergonomics. While these authors help to obtain a structured way of thinking towards objective modes of analysis in HRC, it also appears limited as it relies on solely quantifiable dimensions [33]. In this research, we are concerned with the human factors that impact the individual worker closely interacting with a cobot on the same task. [17] provide a helpful understanding as they divide ergonomics into two bodies: macro-and-micro ergonomics, with the former focused on (company) efficiency and the latter focused on individual-specific ergonomic factors. We expand on this definition of micro-ergonomics by including the other factors that are typically associated with human factors such as environmental factors [14]. In this work, we are examining the human factors that directly relate to the individual and are shaped through interactions between humans, cobots and the environment. As Cobotics comprise of complex socio-technical systems [14], it is necessary to uncover which human factors enrich the design of HRC. These perspectives and motivations were an important prerequisite in identifying appropriate search strategies.

In our search, the challenge arose that prior literature used human factors and ergonomics in overlapping and broadly defined ways [34]. While this research focuses on human factors, it was therefore necessary to include ‘’ergonomics’’ as one of the search terms. In this way, upon further investigation, it was possible to identify whether the contents were suitable for the research objectives pertaining to human factors. Furthermore, given the study’s focus on HRC and Cobotics, the electronic database Scopus was utilised. Prior researchers have identified Scopus as the most prominent database in Cobotics research [6, 19, 22, 35]. We decided to focus on high-quality, peer-reviewed research articles to ensure the quality of the included corpus and to minimise the impact of several publications based on the same dataset [31]. Therefore, our initial search was limited to articles, book chapters and reviews. Based on other literature reviews in the field of HRC, it becomes clear that the majority of research has been produced in recent years [2, 33]. As such, we focused on publications between 2013 and 2023. Finally, we limited the search to English. On the 19th of October, 2023, we applied the following string of keywords: (''Human-Robot Interaction'' OR ''Human-Robot Collaboration'') AND (''Human Factors'' OR ''Ergonomics'') AND (Collaborative Rob* OR Cobot*). This search string with the aforementioned filters generated 166 documents. While this search string was effective in selecting the appropriate body of articles to answer the research question of this review, we applied cross-referencing and snowballing to identify further relevant studies. The snowballing body consisted of high-quality conference papers that provided additional insights into the research question.

2.2 Inclusion criteria and study selection

We considered articles for inclusion if they adhered to the following parameters: (a) discussed human factors or ergonomics (physical and/or cognitive) with the intent to analyse or improve worker conditions in HRC applications, (b) used a human/user-centric approach rather than a technocentric approach and (c) focused on human factors/micro-ergonomic issues of HRC. The overview of inclusion/exclusion criteria for determining the eligibility of documents can be seen in Table 1. The choices for inclusion and exclusion criteria were motivated by the understanding of capturing the human factors in HRC systems, herein targeting the body of literature that deals with the human conditions of closely collaborating with cobots. Consequently, using prior research, we can establish the human factors that enrich the design of HRC.

Table 1. Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Studies with a focus on HRC applications (direct collaboration between human and cobot)	Studies focus on Human-Robot Interaction, rather than HRC (no direct collaboration between human and cobot)
Studies with a focus on physical and cognitive ergonomics with the intent to analyse or improve worker conditions in HRC applications	Studies focus on other aspects of ergonomics such as organisational, safety and product
Studies use a human/user-centric approach towards addressing HRC	Studies use a technocentric approach towards addressing HRC

Studies use a perspective that is consistent with the definition of micro-ergonomics	Studies use a perspective that is consistent with the definition of macro-ergonomics
Publication type: full article, book chapters and reviews	Publication types different from full articles, book chapters and reviews
English language	Languages other than English

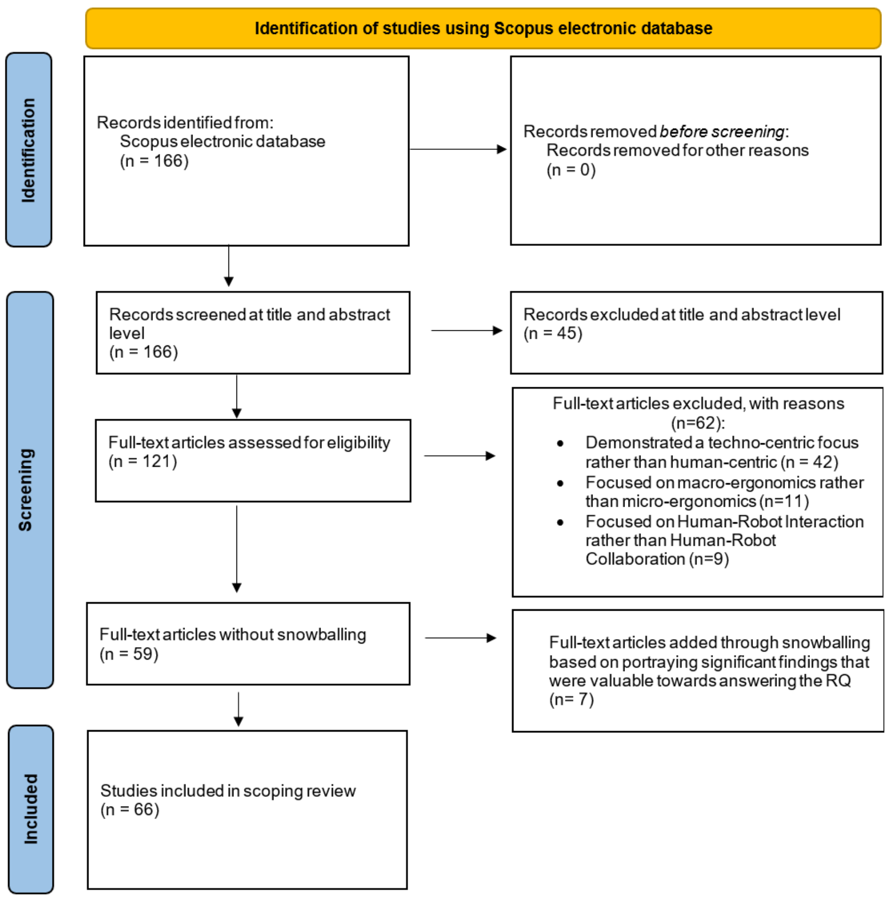

Fig. 1. Flowchart of selection process following PRISMA guidelines for scoping reviews

Using the PRISMA framework for scoping reviews [31]; first, we screened 166 titles and abstracts for eligibility. Based on this initial eligibility check, we deemed 45 articles unsuitable for answering the research question. Second, we performed a full-text analysis using the inclusion criteria. For the following reasons, articles were removed: (a) technocentric approach (n=42), (b) macro-ergonomics (n=11) and (c) Human-Robot Interaction (n=9). This resulted in 59 full-text articles suitable for inclusion in the scoping review. During the full-text analysis, several high-quality papers were identified and deemed helpful in answering the research question. Consequently, 7 papers were added through snowballing. Ultimately, the scoping review consisted of 66 full-text articles. An overview of the PRISMA flowchart outlining the process followed can be found in Fig. 1.

2.3 Data extraction and reporting

The 66 full-text papers were analysed based on how the human factors enriched the design of HRC applications described in the research. Based on the literature, we identified five overarching human factors that enrich the design of HRC: (a) physical factors, (b) cognitive factors, (c) cobot factors, (d) external factors and (e) user acceptance. Rather than perceiving these human factors as subject to quantitative measurements, we provided descriptions for each human factor and subfactor as subject to qualitative measures. During the analysis, we grouped papers to relevant human factors. We also identified subfactors per human factor. The result of this analysis can be found in Table 2. Furthermore, to obtain descriptive statistics of the scoping review, we also extracted the following variables: (a) year of publication, (b) type of publication, (c) country of publication, and (d) primary method.

Table 2. Overview of human factors in HRC as qualitative measurements

Human Factors	Subfactors	Meaning	Relevant works
Physical factors		Human factors that influence the physical state of the human engaging in HRC	
	Physical strain	Relates to the physical strain or exertion experienced in HRC	[4, 12–17, 19–21, 23, 27, 35–50]
	Physical fatigue	Relates to physical fatigue or tiredness experienced in HRC	[4, 13, 15–17, 19–21, 23, 27, 33, 34, 36, 39, 42, 43, 48, 49, 51]
	Posture	Relates to the positioning of the body in HRC	[4, 9, 16, 17, 19–21, 23, 27, 33, 34, 36–38,

			40, 43, 46, 48, 49, 52]
Cognitive factors		Human factors that influence the mental state of the human engaging in HRC	
	Mental strain	This relates to the mental strain experienced in HRC	[4, 12, 13, 15–17, 19, 21–24, 29, 33, 35, 37–39, 41, 42, 45, 50, 53–57]
	Mental fatigue	Relates to the mental fatigue or tiredness experienced in HRC	[4, 15–17, 19, 21–24, 29, 33, 37, 39, 43, 51, 53, 56–58]
	Stress	Relates to levels of stress experienced in HRC	[3, 4, 7, 9, 13, 15–17, 19, 22–25, 29, 33–37, 41, 42, 44, 47, 50, 53, 55–59]
Cobot factors		Human factors that are formed through the qualities of the cobot and its interactions with the human	
	Communication	Relates to cobot attributes that enable implicit and explicit human-cobot communication in HRC and how this is experienced in HRC	[3, 9–13, 16, 17, 24, 26, 28, 33, 35–37, 39, 42, 44–47, 50, 53, 56–72]
	Appearance	Relates to a cobot's appearance and how this is experienced in HRC	[7, 11, 12, 15, 24, 28, 29, 33, 35, 36, 38, 39, 41, 44, 45, 47, 50, 52, 55, 57, 64, 65, 67, 69]

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	Affordances	Relates to a cobot's qualities and actions that enable increasingly complex HRC and can actively shape experience in HRC	[7, 9, 12, 15, 16, 21, 24–26, 28–30, 35, 37, 39, 42, 44–47, 49, 50, 54, 56–58, 64, 65, 69]
External factors		Human factors external to the human and cobot that influence the HRC	
	Task complexity	Relates to the specific circumstances of the task in HRC	[7, 11–13, 15, 16, 21, 26, 30, 34, 36–38, 42, 50, 58, 63–65, 67]
	Environment	Relates to the specific circumstances of the environment where the task of HRC takes place	[7, 9, 11, 13–17, 20, 22, 23, 25, 26, 28, 34–37, 39, 41, 42, 44–47, 50, 52, 56, 58, 63, 65, 67, 70, 71, 73]
User acceptance		The perceived attitude of a human towards HRC and this human factor is informed by physical, cognitive, cobot-specific, and external factors	
	User characteristics	Relates to the individual user characteristics that shape the experience of HRC	[7, 9, 11, 13, 15, 20–22, 24, 28, 30, 34–37, 39, 40, 42, 45–47, 51, 54–56, 58, 64, 65, 67, 69, 70, 73, 74]
	Perceived safety	Relates to how the individual perceives safety in HRC	[13, 15, 19, 22, 23, 33, 35–42, 44, 46, 47, 50, 56–58,

		63, 65, 67, 69, 73, 74]
Perceived trust	Relates to how the individual perceives trust in HRC	[7, 11, 12, 16, 22, 23, 29, 30, 33, 35–42, 46, 47, 49, 51, 52, 55–57, 60, 65, 67, 69, 72–75]

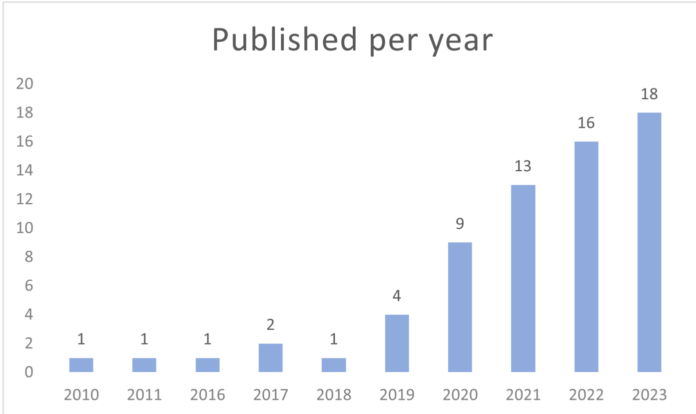
3 Results

As outlined in Figure 1, 66 full-text papers were included in this review. The following subsections delve into the descriptive data, identifying important aspects of the scoping review and discussing the results.

3.1 Descriptive statistics

Fig 2. presents an overview of the descriptive statistics relevant to the conducted scoping review. We extracted the following descriptors: (a) year of publication, (b) type of publication, (c) country of publication, (d) primary method. Fig 2a highlights that the field of human factors in HRC is growing and sees the majority of its publications in the last three years (71%). On the other hand, it becomes apparent that only six papers (9.1%) have been published between 2010-2018. With the Industry 5.0 vision, it could be assumed that the field of human factors in HRC will continue to grow and produce more insights. Furthermore, Figure 2b illuminates the countries included in this study. The scoping review draws on works from 18 different countries; however, most studies originate from Italy (28.8%), followed by Germany (13.6%) and the United States (12.1%). Contrastingly, it is interesting to observe that other big market competitors and developers in the field of Robotics like Japan and China [74], appear to produce little research relating to human factors in HRC (combined n = 4, 6.1%). This reflects the general underrepresentation and underappreciation of studies on human factors in HRC thus far [14, 34, 47]. As can be seen in Figure 2c, the results of the scoping review revealed that most publications are from journals (n = 57), followed by conference contributions (n = 7) and book chapters (n = 2). Our findings indicate that the results from research-related experiments were most frequently published (34.8%), followed by the publication of literature review articles (33.3%). It is important to acknowledge practical limitations such as the adoption and actual use of cobots, which limits the ability to examine real-world applications; for instance, [44] were reliant on user testing with inexperienced participants as the availability of workers who had worked together with a cobot before was limited. Herein, as human factors in HRC are such an emergent research area, conducted research can be highly contextual [74] and is often dependent on the availability of cobots and workers who have experienced collaborating with cobots.

a)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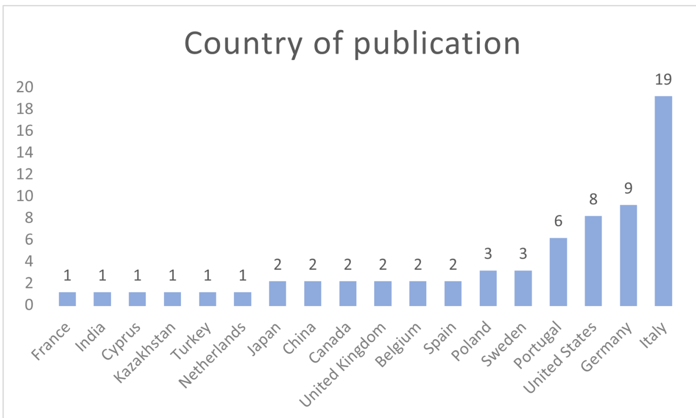
b)


Country of publication
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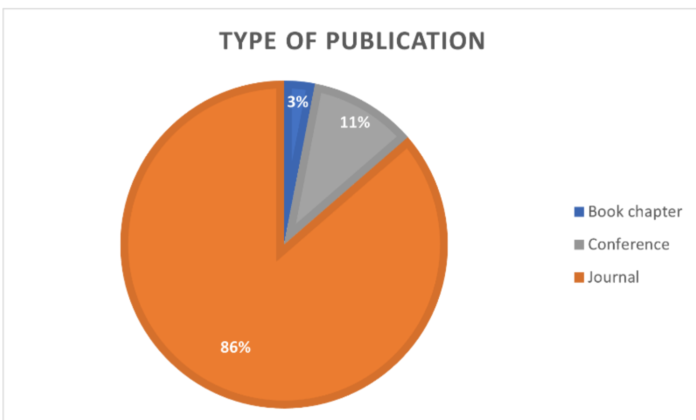
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Conference
Journal

d)

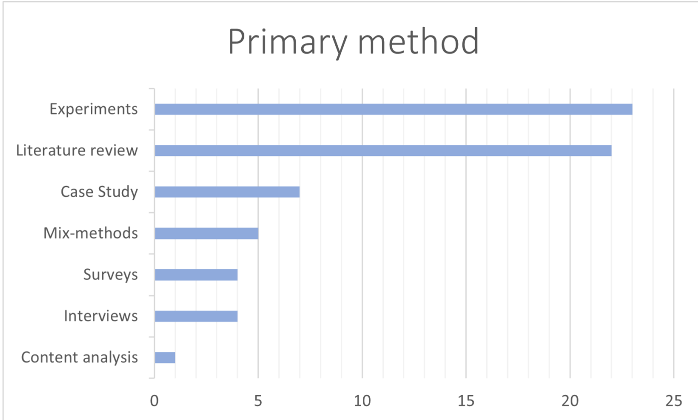

Fig. 2. Distribution of analysed papers (a) per year, (b) per country, (c) by type of document, and (d) by type of method

3.2 Human Factors that enrich the design of HRC

First, the analysis of scoping reviews illuminated the increasing need for the evaluation of individualised experiences of HRC to inform design. This was apparent through the emerging research area of individualised Human-Robot Interaction (iHRI) [41]. iHRI is characterised by the need to evaluate how an individual makes sense of HRC and as such, serves as an overarching methodological perspective to further understand these human-cobot relationships. By capturing individual experiences, it is possible to illuminate the human factors that enrich HRC design; as collaborative processes become increasingly customisable rather than standardised, it is important to consider individual experience to cater to optimal HRC designs and make these designs and interactions customisable as well. Building on this understanding, holistic approaches are required to understand these complex socio-technical designs, as existing holistic efforts are minimal [3, 19, 23, 28, 33, 41, 42]. Consequently, the following subsections outline the human factors that enrich the design of HRC.

3.2.1 Physical and External Factors. With the use of robots moving from large robotic machinery in caged environments to smaller robots capable of direct collaboration, it is logical that much attention of recent research was paid to safety, in particular, physical safety [70]. However, rather than seeing safety as a human factor, safety ought to be treated as a requirement that enables complex HRC [46, 50]. Adopting this approach, the physical factors identified in the literature relate to the bodily, and physical factors of the humans that are impacted by and through HRC [21, 33, 36, 39]. As such, we perceive these as the physical experiences that are caused by HRC. Based on the literature, we identified three subfactors relating to physical factors: (a) physical strain, (b) physical fatigue, and (c) posture [19, 27, 47, 53]. These physical experiences appear to be considerably influenced by external factors such as workplace design and the environment [9, 24, 54].

[48] aimed to produce an ergonomic role allocation framework that optimises HRC, which was tested in an assembly scenario. The physical burden on the body was measured using objective measures (quantitative measures) and the experiences were measured using self-reporting questionnaires [48]. Merlo and colleagues' findings (2023) are consistent with prior findings that HRC applications have the potential to reduce the physical demand on the body of the operator [2, 7, 23]. Similar to Merlo et al. (2023), [21] propose an integrated task allocation model that supports worker well-being in HRC. Through experimental assembly tasks, they find that worker's health is improved through reduced physical fatigue and improved posture [21]. Interestingly, while these findings are consistent with other findings in industrial applications such as manufacturing [38, 49], surgical HRC presents contradictory findings [9]. Beuss and colleagues (2021) identified challenges in workplace design relevant to using cobots in maxillofacial surgery. While the introduction of cobots in surgical environments can yield several benefits, the use of cobots can cause work-induced injuries for surgeons who have to collaborate with cobots in unergonomic positions [9]. It becomes clear that the use of cobots does not produce the same benefits in different environments. As such, the evaluation of physical factors appears to be influenced by external factors such as the space in which the HRC takes place. In other words, based on the design of the space where HRC takes place, physical human factors can be experienced differently across individuals, applications and industries.

3.2.2 Cognitive Factors. HRC with cobots has the potential to greatly improve the conditions of the worker, both physically and mentally [17]. Contrary to working with robots at a distance, when humans are working with cobots in close proximity, a number of cognitive factors are imposed. Based on the literature, we identified the following subfactors: (a) mental strain, (b) mental fatigue and (c) stress [17, 33, 42, 56, 57, 76].

For instance, [4] used a case study to evaluate human conditions in HRC configurations. They show that while the introduction of cobots improves physical human conditions, there is an increase in experienced stress and an overall decrease in mental well-being because of the shift from separation to close interaction with a cobot [4]. [38] performed a case study in which they designed a complex HRC assembly workstation. Through the use of two workstation scenarios in industrial settings, they demonstrated how HRC can decrease the mental workload for users [38]. These findings are supported by [29, 54]. However, [3] found that mental effort was increased in complex HRC scenarios. This contradiction could be explained by [34] who underlines the necessity to evaluate the kind of tasks in HRC (level of complexity). As such, task complexity can be seen as another important human factor enriching HRC designs. Additionally, this portrays how various individuals could experience complex HRC tasks in different ways. This also highlights that these human factors in HRC can be experienced both positively and negatively. As such, there is a lot of potential to uncover these experiences, particularly negative ones, to enrich and improve HRC design to produce a positive impact.

Furthermore, the literature does not only include physical fatigue but also highlights mental fatigue [53, 56]. Mental fatigue can accumulate when workers engage in continuous work or if tasks are repetitive and monotonous [21]. Mental fatigue is typically measured using physiological measures and analysed quantitively [21]. [56] conducted an experiment surrounding cognitive fatigue, workload, gender, and situational awareness. As one of the few works considering the gender of the user, it is interesting to observe that women benefit more from the implementation of HRC but also experience more cognitive fatigue than men [56]. Moreover, [21] provides a cyclical solution to the issue of cognitive fatigue; they highlight how the cobot can support the worker when they feel fatigued, thereby optimising the worker's condition. Cai et al. (2023) stress the need to prevent cognitive fatigue as it can lead to potential errors or injuries. As the topic of cognitive fatigue in HRC is still in its novelty, there is a lot of potential to examine how different kinds of users experience HRC differently, for instance in the degree they experience cognitive fatigue. Finally, as the cobot moves within close vicinity to the worker, workers often experience stress [42, 45, 50]. [59] were one of the first to examine stress induced in HRC tasks. By using an experimental assembly task, they found that users experience stress in HRC tasks and that these levels of stress are influenced by factors specific to the cobot, such as movement speed and communication [59]. This is further supported by later findings in the field, such as [24], who performed a preliminary investigation into the psychological state of workers in HRC and found the cobot's speed to be a major influence towards reported stress levels. In sum, particularly with cognitive factors, it is clear that these factors are user-specific and can be altered over time [42]. Consequently, it is crucial to provide a continuous measurement research design that collects rich insights by capturing user experiences (a) before, (b) during and (c) after collaborating with a cobot [17].

3.2.3 Cobot Factors. In the design of a socio-technical system such as HRC, it becomes clear that experiences are also formed collaboratively; the human and the cobot shape these experiences jointly. Therefore, it is important to consider how the human factors specific to the cobot actively influence and shape the human’s experiences in HRC. As the cobot adopts increasing capabilities and agency, it becomes increasingly vivid that the cobot has the agency to actively shape the experience of the user in a joint interaction [11]. While the user remains central in the HRC activity, it is crucial to consider how the cobot can influence and shape this activity. While significant attention is paid to cobot factors, the importance of such cobot factors remains underexplored [34]. We identified the following subfactors: (a) communication, (b) appearance and (c) affordance [24, 45, 47, 53].

The frequent inclusion of communication in studies, stresses the influences communication can have on HRC [33, 37, 58]. In the current body of literature, the human factor of communication often encompasses how a cobot can communicate its actions through modalities relating to verbal, sound and visual [28]. Coming from a design perspective, several works demonstrate ways in which bi-directional communication streams can be achieved between humans and cobots [28, 63, 71]. For instance, [61] proposes using Augmented Reality (AR) or Virtual Reality (VR) to facilitate communication between humans and cobot technologies, while [72] proposes using ChatGPT to enable cobots to communicate back to the human. As such, these modalities aim to enable visible modes of communication. Therefore, communication is not limited to feedback and task completion but should be viewed more holistically. Herein, it encompasses bi-directional communication during collaborative tasks, also relating to instructions. Furthermore, Cheatle and colleagues (2023) explored how sensory elements of surgeons and surgical teams were affected by robot-assisted surgeries. Their work highlights how the introduction of cobots into certain workplace practices alters sensory experiences, such as the loss of sensory touch during surgeries [63]. Consequently, these losses of senses ought to be compensated through the communication modalities of cobots [63]. Adopting these views on cobot communication underscores the requirements for achieving human-cobot synergy where cobots are perceived as active agents that shape HRC. Furthermore, proper cobot communication increases the perceived sense of safety experienced by users [42]. However, these perceptions and experiences are dependent on how users make sense of both verbal communication modalities, as described above, and non-verbal communication. Prior literature therefore also highlights how cobot's appearance can enrich HRC design, usually relating to size and anthropomorphic features [17, 69]. [39] conducted a survey study with employees of a manufacturing company and found that workers would prefer cobots to exhibit anthropomorphic features. These findings are consistent with a similar study conducted by [69]. It is noteworthy that both these studies demonstrate a correlation between the appearance of the cobot and the perceived levels of acceptance of the user [39, 69]. Finally, another significant cobot factor relates to the affordances of the cobot [26]. For instance, [29] experimented to test experiences with cobots in the manufacturing industry. Rather than seeing autonomy and control as a fixed variable, they stress the need to treat autonomy as perceived autonomy [29]. Their findings illuminate that perceived autonomy is one of the most important human factors in HRC environments [29]. In conjunction with autonomy, it is important to consider the degree of control provided to the user and how users can manipulate this degree of control based on their skill level and experience [29]. Herein, HRC designs need to support flexibility to allow for user customisation [24, 44, 59, 61]. To exemplify, [24] illustrates that in HRC tasks, more experienced workers preferred to increase the speed of a cobot, while inexperienced workers did not need this level of control. Consequently, to adhere to principles of I5.0 such as customisability, HRC designs should become customisable to enrich the experiences of the worker [12, 24, 38].

3.2.4 User Acceptance. In the analysis of human factors in HRC, it became clear that considering user acceptance as a human factor can enrich the design of HRC. We view user acceptance as a crucial component in the achievement of human-robot symbiosis. To achieve this synergy, the view or attitude of an individual towards HRC can significantly impact the way this collaboration is enacted [11]. Moreover, examining user acceptance in consideration of the other human factors outlined in the previous subsections remains largely underexplored in HRC research. This could be explained by the academic debate surrounding the appropriate measurement of user acceptance in HRC. Many works are built on earlier models of technology acceptance such as TAM (Technology Acceptance Model) and

UTAUT (Unified Theory of Acceptance and Use of Technology) ((and other adaptations including UTAUT2)) [67, 74]. For example, [74] developed the Human-Robot Collaboration Acceptance Model (HRCAM) based on a cross-cultural survey study. Their model extends the original TAM model's focus on perceived ease of use and perceived usefulness [74]. However, criticism arises as the model appears not suitable to address the complexity of HRC designs [47, 69]. How users perceive collaboration with cobots appears to be continuous and should therefore be treated as something that can be developed over time [47]. In addition, using HRCAM [74] and other adaptations [47] lacks a holistic understanding of all the components that inform user experiences in HRC designs. Consequently, we propose to evaluate HRC experiences in complex socio-technical systems design by observing how different human factors inform and shape each other, while still considering the individual user traits that are relevant to the collaboration such as gender, experience, age and technological affinity [22, 47, 56, 74, 77]. Adopting this holistic approach can illuminate the human factors that enrich HRC design.

Building on the notion of individualised experiences HRC [41], the literature reveals two subfactors that are particularly important to user acceptance of HRC: (a) perceived safety and (b) perceived trust [7, 30, 50, 67]. This underlines a crucial development in the space of human factors and HRC; rather than objectively stating the safety of the collaboration, the collaboration must be perceived to be safe and trustworthy. [39] suggest that using anthropomorphic cobot designs; a) human-like appearances and b) human-like movements of robot joints and arms can increase the user's safety perception of the HRC task.

Furthermore, [67] performed a recent study where they conducted a literature review on technology acceptance in HRC and a survey study with warehouse workers. They identify perceived safety as a factor in cobot acceptance, while also highlighting the interrelations between perceived safety and trust [67]. Furthermore, these authors stress how more human factors could be informing user acceptance in complex HRC designs such as cognitive factors [67]. Therefore, the inclusion of user acceptance as a human factor that enriches HRC design highlights the need to adopt an individualised approach that considers how various human factors shape HRC differently based on an individual user.

4 Discussion

Human factors in HRC is an emergent research topic that has largely lacked holistic approaches to understanding these complex socio-technical systems [12]. Several trends and opportunities have been identified in the study of human factors in HRC. First, we established human factors that enrich HRC designs using the emergent research field that draws on individualised experience in HRC (iHRI). Herein, the literature revealed opportunities to capture rich experiences that go beyond safety and ergonomics; (a) physical factors, (b) cognitive factors, (c) cobot factors, (d) user acceptance and (e) external factors. Second, these human factors can offer new insights through qualitative inquiries, as existing efforts are predominantly quantitative. Herein, individualised experiences can be analysed to inform human factors in HRC designs. Additionally, it is revealed that these factors appear to be interrelated and can inform each other. Therefore, a rich description of these HRC systems can expose how these human factors are formed in these experiences. Finally, it is highlighted that human factors in HRC, when perceived as experiences, are highly contextual and user-specific. Therefore, this should be reflected in HRC designs, allowing for customisability and flexibility that further support the potential of synergy in HRC applications.

Based on the research findings, we developed a conceptual framework that provides a structured way of thinking when analysing experiences in HRC to enrich HRC designs. While we used the model developed by [78] as a reference model, the content of the proposed framework is based on the research findings and builds on previously developed models [15, 33, 50, 64]. Fig. 3 presents the conceptual framework and contains the five overarching human factors that enrich HRC design. Fig. 3 highlights the need to evaluate these human factors in relation to each other, and rather than evaluating them separately, it is crucial to examine how these human factors are rooted in user-specific experiences. It should be noted that for these human factors and subfactors, there are existing quantitative measures, such as physical exertion [49]. However, in this work, we stress the importance of developing and using qualitative approaches towards analysing human factors in HRC. Researchers and industry practitioners can use this conceptual framework as a structured way of thinking when investigating HRC experiences to enrich human factors in HRC design. For instance, the different factors can be used as themes in deductive, thematic analyses of HRC experiences. As such, the conceptual framework supplements and supports the need for more empirical research approaches towards analysing human factors in HRC designs.

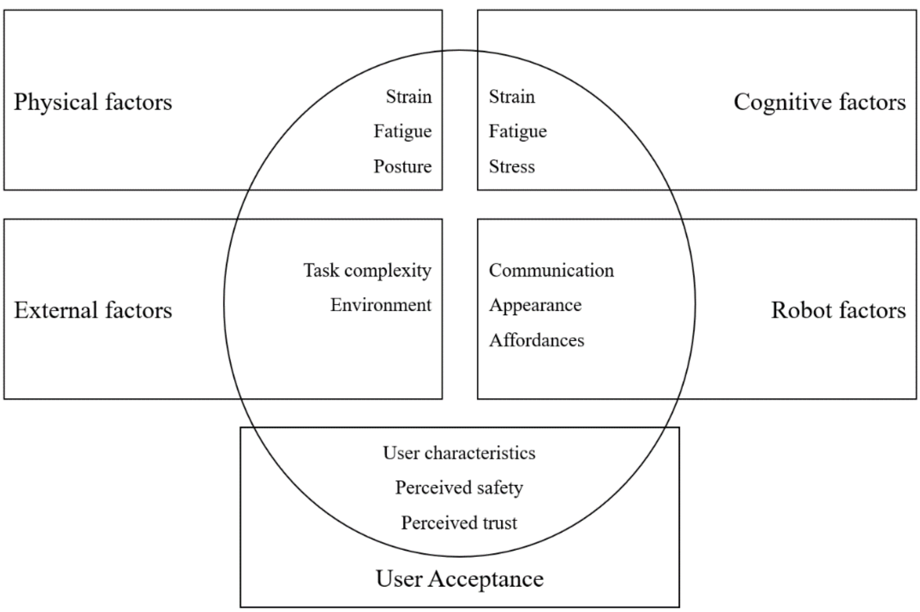

Fig. 3. Conceptual framework to examine human factors in HRC through experiences

5 Conclusion

In this paper, we presented a scoping review to identify the human factors that enrich HRC design. At its core, Cobotic socio-technical systems are complex and can be found in a variety of industries and different applications. As these socio-technical systems aim to capitalise on the synergy that can be created between humans and cobots, it is crucial to understand how we can support and evaluate human factors that enrich HRC designs. Using the PRISMA extension for scoping reviews, we used a systematic and rigorous approach to find and select relevant papers to answer the research question. After following the PRISMA protocol, we analysed 66 full-text papers.

This review highlighted several trends and opportunities in the field of human factors and HRC. First, it became clear that the field of human factors has mostly consisted of safety and ergonomics. There is an opportunity to go beyond these lenses by encompassing more human factors that are rooted in user experiences with HRC. As such, we identified the growing need to evaluate individualised experiences towards understanding human factors in HRC. Based on the literature, the human factors that enrich HRC design consist of (a) physical factors, (b) cognitive factors, (c) robot factors, (d) external factors and (e) user acceptance. Using these findings, we presented a conceptual framework that illustrates how these factors are interrelated in the individual experiences of a user in HRC, and we illuminated how this framework can be used to examine human factors that enrich HRC designs. These research findings are valuable as they support the need to examine human factors in HRC more holistically and these findings assist in providing more individualised approaches towards understanding human factors in HRC. Simultaneously, these findings open the path towards obtaining positive user experiences with HRC, which could support the adoption and implementation of HRC.

5.1 Limitations and Future Research

It is essential to identify the potential limitations of this study. Despite following the PRISMA guidelines, some works may have been omitted in this review. For instance, as the scope of this research is HRC rather than HRI, it is possible certain types of cobots have not been included, such as studies that examine human factors when using exoskeletons. Therefore, future research could use these findings and discuss other types of cobots omitted from these works to support further the conceptual framework's goal of a more holistic approach towards human factors in HRC designs. Additionally, the bottom-up approach of this scoping review, identifying human factors in HRC designs, can be seen as limiting. Although beyond the scope of this work, future works could compare the research findings with top-down approaches produced in other relevant bodies, such as CHI, focusing more on interaction design and the design for experience [12], on which some of these findings are based. Furthermore, as little empirical research has been conducted on human factors in HRC, it is evident that the proposed conceptual framework lacks empirical support. As such, future research is needed to validate the conceptual framework in real-world applications of HRC. This could assist in clarifying the interrelationships between factors as well as clarify various subfactors. The conceptual framework produced in this work should be seen as the first step toward a structured way of thinking within the design of HRC spaces, but this framework will quickly evolve through future works.

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