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Updating design guidelines for cognitive ergonomics in human-centred collaborative robotics applications: An expert survey

Luca Gualtieri[a,*], Federico Fraboni[b], Hannah Brendel[b], Luca Pietrantoni[b], Renato Vidoni[a], Patrick Dallasega[a]

[a] *Industrial Engineering and Automation (IEA), Faculty of Engineering, Free University of Bozen-Bolzano, Piazza Domenicani 3, 39100, Bolzano, Italy*
[b] *Department of Psychology, Università di Bologna, Via Zamboni 33, 40126, Bologna, Italy*

A R T I C L E I N F O

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A B S T R A C T

Within the framework of Industry 5.0, human factors are essential for enhancing the work conditions and well-being of operators interacting with even more advanced and smart manufacturing systems and machines and increasing production performances. Nevertheless, cognitive ergonomics is often underestimated when implementing advanced industrial human-robot interaction. Thus, this work aims to systematically update, develop, and validate guidelines to assist non-experts in the early stages of the design of anthropocentric and collaborative assembly applications by focusing on the main features that have positively influenced workers' cognitive responses. A methodology for structured development has been proposed. The draft guidelines have been created starting from the outcomes of a systematic and extended screening of the scientific literature. Preliminary validation has been carried out with the help of researchers working in the field. Inputs on comprehensibility and relevance have been gathered to enhance the guidelines. Lastly, a survey was used to examine in depth how international experts in different branches can interpret such guidelines. In total, 108 responders were asked to qualitatively and quantitatively evaluate the guideline's comprehensibility and provide general comments or suggestions for each guideline. Based on the survey's results, the guidelines have been validated and some have been reviewed and re-written in their final form. The present work highlights that integrating human factors into the design of collaborative applications can significantly bolster manufacturing operations' resilience through inclusivity and system adaptability by enhancing worker safety, ergonomics, and wellbeing.

1. Introduction

In the upcoming years, an increasing number of workers will engage in collaboration with industrial robots to fulfil their work activities (Smids et al., 2020). While robots offer support to humans in performing stressful and demanding tasks, serving as physical or cognitive aids, the interaction between industrial robots and humans (iHRI) poses potential emerging risks in sociotechnical systems (Rosen et al., 2022).

Consequently, social sustainability will be even more crucial in modern and future collaborative robotics applications. Sustainability is a multidisciplinary branch that includes environmental, social, and economic dimensions (Braccini and Margherita, 2018), constituting a fundamental "Industry 5.0" element. The fifth industrial revolution aims to locate employees' well-being at the centre of the factory and reinforce the contribution of industry to society by using digital and artificial intelligence-based technologies (Braccini and Margherita, 2018). Human centricity, sustainability, and resilience are promoted over efficiency and productivity (Breque et al., 2021; Nahavandi, 2019). In particular, the anthropocentric approach highlights how technologies can customize the work according to human needs and wants. Industry 5.0 recognizes tailored human-machine interaction that integrates the capabilities of both humans and machines as one of its key factors (Müller, 2020; Maddikunta et al., 2022a). It means that machine-based manufacturing systems adjust to the requirements and diversity of employees rather than necessitate continuous adaptation by the workers to ever-evolving technology.

Collaborative robots (cobots) can be an effective solution for implementing such inclusive workplaces. They allow the implementation of anthropocentric and adaptable applications based on iHRI by considering the primary user's needs (e.g., training level, personal capabilities, age, anthropometric features, etc.) and wants (e.g., preferences, wishes, volunteer feedback, etc.) with the final goal of improving

* Corresponding author.
E-mail address: luca.gualtieri@unibz.it (L. Gualtieri).

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safety, ergonomics and production performances. However, given the inherent psychosocial risk, it is necessary to design iHRI by carefully considering the industrial application, as well as the influence of the robotic system on the psychophysical condition of the operator (Panagou et al., 2023), particularly in the most advanced forms. The cognitive effects must be considered, especially regarding robot autonomy, understandability, reliability, and anthropomorphism. In that regard, most companies ignore or cannot effectively handle such complicated ergonomic-related challenges. This implies unsuitable work conditions for the operators and a barrier to companies' successful and widespread implementation of collaborative applications. Hence, further research in this field is still required. Thus, this study proposes a systematic methodology for developing and validating a comprehensive set of guidelines to assist non-experts in human factors and cognitive ergonomics (HF&CE) (e.g., industrial engineers, roboticists, and system integrators) in the early stages of the design of anthropocentric and collaborative assembly applications.

A systematic literature review was conducted on relevant findings concerning HF&CE in iHRI. Based on the results, the design principles (i.e., guidelines) have been systematically drafted while considering the target group and final objective. The draft guidelines underwent an initial evaluation by an independent team of scholars studying iHRI. According to the feedback we received, the guidelines have been revised. Subsequently, a survey has been formulated to comprehensively explore how international experts from various disciplines can interpret and assess the updated guidelines. Finally, specific criteria used for the classification and evaluation of the guideline's comprehensibility have been defined, and the guidelines have been revised by considering the quantitative and qualitative feedback of the experts.

The present work directly stems from previous studies (Gualtieri et al., 2021, 2022, 2023a; Panchetti et al., 2023). The domain of iHRI is an ever-evolving field that necessitates continuous refinement and reassessment of design guidelines addressing HF&CE, given the surge in novel studies. Building upon our previous work, this article introduces novel research questions that probe further into the applicability and efficacy of guidelines for designing anthropocentric collaborative applications. We have adopted an advanced methodological framework, distinct from our earlier efforts, allowing for a nuanced collection and analysis of data that offer fresh perspectives. With a commitment to academic integrity, we have meticulously ensured that any overlapping concepts with our prior work are explicitly cited, maintaining the literary uniqueness of the current manuscript. In this manuscript, we present the continuation and evolution of our research. The following sections will delineate this study's specific methodological advancements and empirical contributions.

2. Literature review

2.1. Human-robot interaction in industry 5.0

Cobots can be used as assistance systems to support and enable the user in repetitive, physically, or mentally demanding activities. This enables the worker to concentrate on activities with high added value, caracterized by high dexterity, adaptability, and decision-making abilities. On the other hand, it is vital to prevent the emergence of new risks associated with iHRI (Berx et al., 2022).

The European Commission has recently delineated the key goals of Industry 5.0, emphasizing a human-centric strategy that underscores the need for technology to be employed in adjusting work processes according to the state and behavior of users. This implies that manufacturing systems should adjust to meet the diversity of employees. (Maddikunta et al., 2022b). Given the goals of Industry 5.0 and the capabilities of advanced collaborative robots, it is crucial to employ machines that align with workers' preferences and needs concerning safety, ergonomics, and well-being.

Operators' needs, wants, and perceptions must be considered key human factors in designing and developing advanced iHRIs (Faccio et al., 2023). Overlooking cognitive ergonomics poses numerous risks for the operator and results in a significant deterioration of working conditions. (Pini et al., 2016). In addition, the complexity of modern technologies empowering cobots, such as Artificial Intelligence (AI), is increasing as new and unforeseen perils emerge (Caruana and Francalanza, 2023).

However, human factors, especially cognitive ergonomics, are still frequently underestimated. This is a serious shortcoming since the operators are supposed to physically interact with even more intelligent and autonomous systems (Thorvald et al., 2017a). An extensive body of literature demonstrates that human factors significantly impact operators' well-being, safety, and work-related performance (International Ergonomics Association (IEA), 2020). Therefore, it is crucial for designers to incorporate cognitive ergonomics into the development of future collaborative systems that are both human-centred and efficient (Prati et al., 2021a; Kadir and Broberg, 2021). HRI entails profound changes in production systems (Faccio et al., 2023) as it potentially introduces ergonomics-related issues, including, for instance, cognitive overload (Kong, 2019), stress (Cascio and Montealegre, 2016), information overload (Czerniak et al., 2017), frustration and diminished motivation (Adam et al., 2018), and unsafe work conditions (Liu et al., 2020). Conditions that impose cognitive strain imply occupational hazards to workers' health, safety, and well-being, adversely impacting work performance and productivity (Kalakoski et al., 2020). These adverse conditions are directly associated with the adoption of emerging technologies, the organization of work activities, and how workers interact with production systems, such as human-machine interfaces. In this regard, factors such as trust towards robots (Hopko et al., 2023), acceptance (Zanchettin et al., 2013), and teaming (Adriaensen et al., 2022) have been preliminarily explored in the context of social and iHRI.

2.2. Human-factors in industrial human-robot interaction

In the study of Winfield et al. (Winfield et al. (2021), the authors investigated accidents in HRI with social robots. They highlight that human behaviour plays a crucial role in accident dynamics and prevention. Even if this work refers to social robotics, considering the latest enhancements in AI and industrial collaborative robotics (i.e. the introduction of several industrial humanoid robots in the shopfloor (Will Knight, 2023)), this analysis is also relevant for the industrial sector. Other authors proposed a study that reviews twenty-five articles to understand the impact of human-robot collaboration on workers' mental stress and safety awareness. This research identifies critical robot-related factors that influence these aspects and evaluates different approaches to measuring mental stress and safety awareness in collaborative settings, offering insights to improve operators' work conditions (Lu et al., 2022). In a prior study (Fraboni et al., 2021), the authors emphasized the importance of providing technicians with seamless and intuitive support to consider cognitive requirements while developing advanced collaborative applications. Companies prefer simple approaches to occupational health and safety rather than complex and advanced tools and methods such as those often indicated in the scientific literature (Huck et al., 2021). From the safety perspective, designers frequently encounter uncertainty regarding the proper steps or procedures to manage risks (Chemweno et al., 2020).

Nevertheless, starting from the design, the specifications should be imposed considering the application requirements the envisioned iHRI has to deal with through an iterative process (Zacharaki et al., 2020). In industrial engineering, technical standards and deliverables (CENELEC, 2020) are frequently employed to assist organizations in fulfilling design specifications. These standards typically include guidelines for developing state-of-the-art products, systems, and services. However, excluding certain parts of ISO TR 9241-810 (International Organization for Standardization, 2020), there is a lack of standards explicitly addressing the design of anthropocentric and cognitive-oriented manufacturing systems in which humans and robots interact (Fletcher et al., 2020).

While implementing iHRI, many crucial relationships must be considered between the robotic system design, application features, and related effects on the operator's psychophysical status and behaviour (Panagou et al., 2023; Panchetti et al., 2023). Nevertheless, nowadays, most companies are not able to properly manage such complex ergonomic-related issues, or they ignore them voluntarily or unconsciously. The main reasons are that designers (e.g., industrial engineers, roboticists, and system integrators) generally do not have the necessary knowledge about interdisciplinary topics related to iHRI (Aaltonen and Salmi, 2019; Fraune et al., 2022), underestimate the complexity of the problem (Kopp et al., 2021) or do not have practical tools for the proper assessment of the impact of iHRI on workers (Apraiz et al., 2023; Li et al., 2023), especially from a cognitive perspective (Lorenzini et al., 2023; Kolbeinsson et al., 2019). This situation is even complicated by the possibility of implementing AI-based systems that are increasingly autonomous and able to interact with humans in unstructured environments (Maddikunta et al., 2022a; Macrae, 2022), especially if such systems are not designed to be human-centred and ethical (Kadir and Broberg, 2021; International Organization for Standardization, 2020).

2.3. *Designing resilient and human-centred collaborative applications*

According to (Aruväli et al., 2023), resilience can be considered an engineering system property that supports functional requirements such as safety, sustainability, quality, and flexibility. Resilience in manufacturing is the capacity of a company to foresee, prepare for, react to, and recover from disruptions or changes in a manner that sustains or swiftly restores critical operations, adapts to new conditions, and thrives on uncertainty. Several works discussed the requirements of a resilient production system. In the work of Hosseini et al. (2016), features to model a system's resilience based on absorptive, adaptive, and restorative capabilities are proposed. In another work, Komesker et al. (2022) defined the features of a system to implement a resilient production by identifying modularization, adaptability, scalability, communication capabilities, and effective control mechanisms as critical factors. Furthermore, Fowler et al. (2023) defined desirable factors for resilient manufacturing systems: Reliability, flexibility, adaptability, reconfigurability, robustness, security, and ambidexterity.

Focusing on occupational health and safety, Penaloza et al. (2020) developed "Guidelines on Safety and Performance Management Systems" (SPMSs), offering a clear and system-focused viewpoint for safety management design and applying Resilient Engineering for their evaluation. In addition, Disconzi and Saurin (2024) developed "Design for Resilient Performance" (DfRP) principles to be used by human factors and resilience engineering communities. Their proposal has been validated by analysing the literature on work systems design, a Delphi study, and a case study in healthcare. Furthermore, in another work (Disconzi and Saurin, 2022), they developed and applied a framework to evaluate the application of DfRP principles by using the study of an emergency department as a case study. The study adds to the theory of DfRP while presenting a novel method for evaluating resilience in sociotechnical contexts.

Anthropocentric collaborative robotics is a key technology for implementing resilient engineering in manufacturing systems. HRI is crucial for advancing Industry 5.0, which poses resilience as one of its key pillars by properly integrating machines, technology, and humans (Aheleroff et al., 2022). In that regard, it significantly enhances productivity within a manufacturing setting. By automating repetitive and routine tasks supporting humans as assistance systems, cobots allow workers to focus on higher-value and complex activities (Gualtieri et al., 2023b). This heightened productivity ensures that essential operations continue smoothly, even during disruptions (resilience objective of preserving efficiency and effectiveness during time). In many applications, collaborative robots embody flexibility and cost-effectiveness. They can be easily reprogrammed and adapted to various tasks, enabling rapid adjustments to changing market demands or production requirements (Dmytriyev et al., 2022). This flexibility, combined with cost efficiency, supports a company in adapting swiftly and conveniently to disruptions or unforeseen circumstances (resilience objective of maintaining business continuity and recovering quickly from disruptions). Moreover, cobots contribute to employee safety and well-being by undertaking hazardous or strenuous tasks. By creating a safer work environment, they help protect employee health and safety, ensuring a functional workforce (Aheleroff et al., 2022) (resilience objective of safeguarding the workforce). Finally, iHRI generates substantial operational data. Analyzing this data allows for informed decision-making, aiding in timely adjustments and mitigating the impact of disruptions (Dmytriyev et al., 2022) (resilience objective of enabling informed responses through data-driven decision-making).

2.4. *Research gaps and questions*

To sum up, despite the growing interest among the scientific community, human-centred design and ergonomics in iHRI remain fragmented and predominantly prototypical, still primarily oriented to research applications. Therefore, there is a need for further investigation into supporting companies' designers in the development of advanced collaborative robotic applications following Industry 5.0 principles. In particular, according to the state-of-the-art and considering main requirements in terms of social sustainability, it is evident that (i) cognitive ergonomics and human-centred design are usually neglected when designers (e.g., industrial engineers, roboticists, system integrators) implement iHRIs, and that (ii) effective, simple and updated tools for supporting non-experts on that topics are missing. To fill these research gaps, the presented work seeks to respond to the following research questions:

RQ1: *When designing collaborative applications, which fundamentals of cognitive ergonomics and human factors should be taken into consideration?*
RQ2: *How can guidelines be developed to effectively address non-experts' challenges in integrating human-centred design principles into advanced HRIs within industrial settings?*
RQ3: *How can the feedback from different experts be incorporated into the validation and refinement of these guidelines?*
RQ4: *How do these guidelines contribute to social sustainability and resilience in manufacturing environments?*

The current work addresses the distance between theoretical studies and their real-world applications in advanced iHRIs by updating and validating design guidelines developed for real-world applicability, helping translate academic concepts into actionable strategies for industrial applications. By proposing guidelines accessible by non-experts in HF&CE, the present work advances social sustainability by democratising human-centred design in industrial robotics and highlighting the sometimes-overlooked field of human-factors. The study's approach encourages interdisciplinary cooperation, guaranteeing that the final guidelines are effective, user-friendly, and representative of expert perspectives. In addition to providing a solid basis for developing worker-centric, socially sustainable robotic systems, this work sets a significant precedent for upcoming research in the field. It is essential for enhancing industrial competitiveness and adaptability following Industry 5.0 principles. By ensuring that new technologies are developed with human factors in mind, the present work contributes to creating more sustainable, inclusive, resilient and worker-friendly industrial environments.

3. Method for guidelines development and validation

An interdisciplinary team of researchers with prior experience in the field, comprising industrial engineers and occupational psychologists, has developed the proposed guidelines, inspired by the approach proposed by the "National Institute for Health and Care Excellence" (Ogden, 2017). The overall method is summarized in Table 1. It aims at (i) developing, (ii) revising and updating, and (iii) validating the guidelines by using four sequential phases and encompassing three independent groups. Details are provided in the following sub-sections.

3.1. Phase 1: Systematic analysis of the scientific literature

A systematic analysis of the scientific literature was conducted to identify relevant findings and emerging evidence concerning HF&CE in iHRI. Specifically, a total of 720 papers published between 2020 and 2022 were analyzed using Scopus as the primary database. This interval has been selected since the authors' previous work (Gualtieri et al., 2022), which is the starting point of the present one, has already analyzed the situation before the selected period. It is also necessary to underline that, in the last years, the scientific community has explored such topics extensively, resulting in a considerable increase in published documents. As not all studies identified through the search query are eligible for detailed review, the studies were evaluated against predefined exclusion criteria. Thus, studies were excluded if they investigated (i) healthcare robots, (ii) social robotics (e.g., humanoids for social applications, robots designed for interaction with children or older adults or people with disabilities, etc.), (iii) teleoperated robots, (iv) virtual robots, (v) exoskeletons, (vi) human-robot task allocation. Following an internal discussion, articles addressing the previously mentioned topics were incorporated exclusively if related studies were deemed highly relevant or had broad applicability. The articles that remain after undergoing this filtering process are recorded in the reference list (from (Kopp et al., 2022; Mukherjee et al., 2022; Simões et al., 2022; Borges et al., 2022; Pinheiro et al., 2022; Quinlan-Smith, 2022; Čorňák et al., 2021; Dzedzickis et al., 2021; Ortenzi et al., 2021; Salm-Hoogstraeten and Müsseler, 2021; Khamaisi et al., 2021; Hancock et al., 2021; Schoeller et al., 2021; Selvaggio et al., 2021; Cini et al., 2021; Sarthou et al., 2021; Weiss et al., 2021; Diamantopoulos and Wang, 2021; Bolano et al., 2021; Li et al., 2021a; Dimitropoulos et al., 2021; Castro et al., 2021; Chacón et al., 2021; Grushko et al., 2021; Pollak et al., 2021; Li et al., 2021b; Rossato et al., 2021; Käppler et al., 2020; Rothstein et al., 2020; Hannum et al., 2020; Mizrahi et al., 2020) to (Beschi et al., 2020; Bhalaji et al., 2021; Bounouar et al., 2022; Bounouar et al., 2020; Buxbaum et al., 2020; Chacón et al., 2020; Colim et al., 2020; Colim et al., 2021; Cunha et al., 2020; Dehkordi et al., 2021; Fischer and Sträter, 2020; Fruggiero et al., 2020; Hagenow et al., 2021; Han et al., 2021; Komenda et al., 2021; Lasota and Shah, 2015; Messeri et al., 2020; Prati et al., 2021b; Proia et al., 2021; Ramaraj, 2021; Subrin et al., 2019; Dani et al., 2020; Abrams and der Pütten, 2020; Gyöngyössy et al., 2020; Domonkos et al., 2020; Antonelli et al., 2021; Baltrusch et al., 2021)). The PRISMA flowchart (Page et al., 2021), which summarizes the abovementioned systematic review, is presented in Fig. 1.

3.2. Phase 2: Guidelines development and integration

Based on the results derived from the analysis of scientific literature, the guidelines have been developed while taking into account the target group and final objective of this work. The development and integration were carried out in seven steps, as explained in Fig. 2.

3.3. Phase 3: initial revision and interim update of guidelines

Preliminary evaluation of the guidelines has been carried out with the help of external researchers in manufacturing system design and iHRI (Department of Industrial and Manufacturing Engineering, University of Malta). Qualitative feedback on importance and understandability was gathered to improve the initial iteration of the guidelines before proceeding with further investigations. In total, 53 guidelines have been created and classified into five different categories: Workstation and Robot System Features (i.e., workstation layout, set-up of equipment and devices, the appearance of the robotic system), Robot System Performance and Interaction Patterns (i.e., robotic system's behaviour, interaction modalities between the operator and the robot to perform tasks together), Human-Robot Communication and Interfaces (i.e., communication model, explanation of robotic system's decision and feedback modality), Control Measures (i.e., commands and requests given by the operator to the robotic system), and Organizational Measures and Training (i.e., management of the technology and workforce).

3.4. Phase 4: Extended review based on the expert survey and guidelines final update

The research team developed an online survey using the Qualtrics platform to examine how international experts in various fields (i.e., industrial engineering, robotics, the safety of machinery, human factors/ergonomics, or work and organizational psychology) can evaluate the guidelines. The guideline's comprehensibility has been assessed with a single item (Considering the target group, how comprehensible do you think this Guideline is?) with answers on a 5-point Likert rating scale (ranging from *not at all* to *extremely*). Respondents who reported a comprehensibility score of 1 or 2 were asked to state their opinion on why they deemed the guideline insufficiently comprehensible in an open response format. Furthermore, they have been asked to provide suggestions, again using an open response format, regarding the comprehensibility of the guidelines and any related recommendations for improvements. As a total of 53 guidelines were included in the questionnaire, participants were randomly assigned five guidelines to comment on, resulting in 30 questions on the guidelines per participant. That way, questionnaire fatigue and low-quality and/or inaccurate feedback were aimed to be reduced. Guidelines were randomly assigned to participants. An embedded function of the survey platform that balances out the number of respondents for each guideline was employed to avoid having huge differences in the number of respondents per guideline. Starting from the results, the guidelines have been reviewed and written in their final form. The criteria presented in Table 2, supporting the feedback analysis and the related revision process, have been used for the evaluation of the guidelines' comprehensibility.

Table 1
Summary of the four phases used to develop, revise, update, and validate the guidelines by considering the involved groups.

Phase	Objective			Involved group		
	Development	Revision and update	Validation	Interdisciplinary research team	External research team	Experts in the field
Systematic analysis of the literature	X			X		
Guidelines development and integration	X			X		
Initial revision and interim update of guidelines		X		X	X	
Extended review based on the expert survey and guidelines final update		X	X	X		X

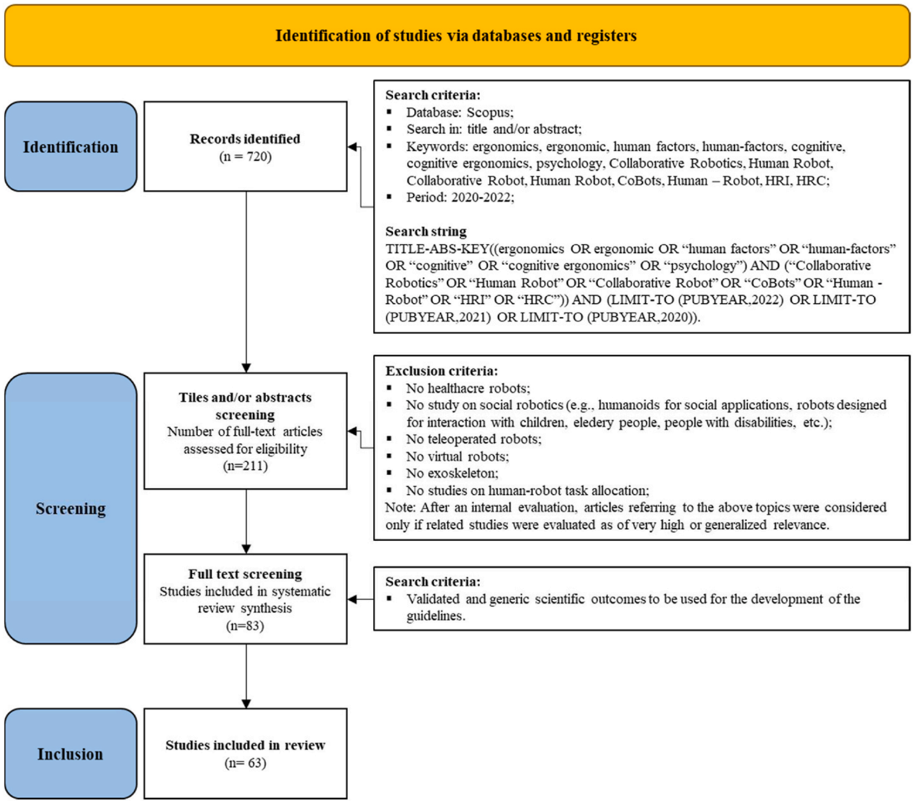

Fig. 1. PRISMA diagram of the systematic literature review gathered to develop and update guidelines.

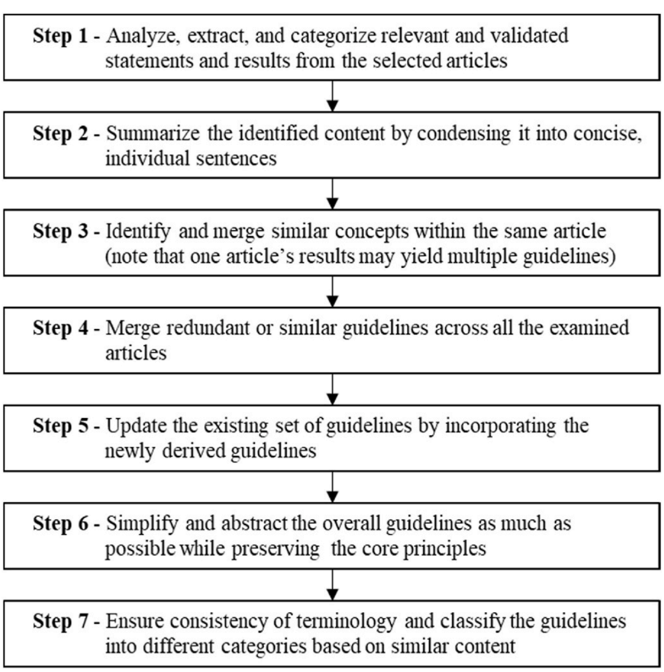

Fig. 2. Seven-steps approach for the development of the guidelines.

The criteria defined in Table 2 have been used to classify the "revision priority" of the guidelines (i.e., "Approved as it is", "Minor revision", "Major revision", or "To be discussed"). Starting from the structured results given by the survey, the proposed hierarchy allows the research team to understand the number, importance, and type of changes required to update the guidelines. This approach considers the combination of the number of respondents (N), the mean comprehensibility values (C_M), and the related standard deviation (SD_{CM}). The relationships between the criteria used for the evaluation of the guideline's comprehensibility and related revision priority are presented in Table 3.

The cases where N is lower than five respondents required particular attention (only three guidelines had this issue, all with $N = 4$). The survey was designed so that at least five experts could randomly evaluate each guideline. According to the research team's experience, this number can be considered satisfactory to have reliable data. Nevertheless, it was impossible to guarantee this condition for all the guidelines. For this reason, the guidelines belonging to this category have been carefully evaluated by the research team by qualitatively analyzing the feedback obtained from the responses to the survey's open items. The multidisciplinary research team carried out the revision process through open discussions supported by quantitative data (C_M, SD_{CM}) and qualitative data (feedback on the comprehensibility of guidelines and related possibilities for improvements).

The research team determined cut-off values for comprehensibility scores to streamline the revision of design guidelines. The survey item investigating comprehensibility ranges from 1 to 5, with higher scores indicating better comprehensibility. The team defined three thresholds: A score of 3.5 or above signified high comprehensibility, suggesting generally positive feedback. Scores between 3 and 3.5 were seen as good but indicated a need for minor improvements. Scores below three were categorized as not easily comprehensible, highlighting the need for major revisions. These cut-offs were chosen to effectively gauge and enhance the clarity of the guidelines based on expert opinions.

Alongside comprehensibility scores, the standard deviation (SD_{CM}) was evaluated to understand the level of consensus among experts. Although there is no general rule of thumb for high or low *SDs*, the chosen cut-off values were established to understand the level of agreement between participants who evaluated the specific guideline. Lower SD_{CM} (≤ 1) indicated a strong agreement on a guideline's comprehensibility, while higher SD_{CM} suggested varying opinions,

Table 2
Criteria used for the evaluation of the guideline's comprehensibility.

Name	Symbol	Description
Nr of respondents for the specific guideline	N	The value was obtained directly from the survey.
Mean comprehensibility of the analyzed guideline	C_M	The value was obtained directly from the survey. The "Mean comprehensibility" of the analyzed guideline was evaluated through the survey using a 5-point Likert scale. The question was, "*Considering the target group, how comprehensible do you think this Guideline is?*"
The standard deviation of the mean comprehensibility values	SD_{CM}	$SD_{CM} = \sqrt{\frac{\sum_{i=1}^{M}(C_i - C_M)^2}{(N-1)}}$ Where: Ci = Each recorded value of comprehensibility of the specific guideline; C_M = Mean comprehensibility of the specific guideline; N = Total number of recorded values of the specific guideline.
Qualitative discussion	/	Feedback was received from open questions on the guidelines' comprehensibility and related possibilities for improvements. The open questions were: (i) "*Why do you think this Guideline is not sufficiently comprehensible?*" and (ii) "*Do you have any comments or suggestions about this Guideline?*".

necessitating revisions. Cut-offs were set at $SD_{CM} \leq 1$ for high consensus, $1 < SD_{CM} \leq 1.5$ for minor disagreements, and $SD_{CM} > 1.5$ for significant divergences requiring major revisions. These cut-offs were specifically chosen based on the survey's nature and the goals of the comprehensibility assessment, highlighting that such thresholds may vary with different research contexts. Table 4 illustrates three examples of how the guidelines have been revised according to their scores and selected cut-offs.

4. Results

4.1. Analysis of survey responses

The sample consists of $N = 108$ participants with a Mean Age of $M_{\text{Age}} = 39.44$ (Standard Deviation $SD = 12.059$), from which 31.5% were female ($n = 34$), 65.7% male ($n = 71$), and 2.8% preferred not to answer ($n = 3$). The average respondent's expertise in robotics/industrial collaborative robotics and familiarity with the main topics covered by the guidelines are reported in Figs. 3 and 4, respectively.

As reported, based on a 5-point Likert scale, respondents' average knowledge about robotics (in general) and industrial collaborative robotics (in specific) is 3.58 and 3.37, respectively. There is a good balance between the different skills and areas of expertise of the respondents (2.84 for "Robot Design and Control"; 2.6 for "Safety of Machinery"; 2.4 for "Work cell Design/Systems Integration"; 2.52 for "Software and System Architecture"; 3.14 for "Human Factors"; 3.19 for "Human-Machine Interface"; 2.61 for "Sensor Technology"). Considering all the topics, the average knowledge of respondents is 2.76. In particular, the topics "Human Factors" and "Human-Machine Interface" are the most familiar to the respondents, while the topics of "Work cell Design/Systems Integration" and "Software and System Architecture" are the less-known ones.

In the following, according to the guideline's evaluation criteria presented in Table 2 and considering the logic proposed in Table 3, Fig. 5 summarizes the revision priority of the guidelines.

As reported, 38% of guidelines have been considered as understandable (as they are) by the target group. Therefore, no modifications are required. 21% of the guidelines have been considered not totally understandable by the target group, so minor revisions are requested. 17% of the guidelines presented a vital lack in terms of understandability; therefore, major revisions are requested. Finally, 25% of guidelines needed further analysis according to the qualitative feedback of the respondents. In particular, only three guidelines did not satisfy the criteria related to the minimum number of respondents ($N < 5$), while the other ten guidelines need further discussion due to unsatisfactory values in terms of mean comprehensibility ($3.5 > C_M \geq 3$) and/or standard deviation ($1 > SD_{CM} \geq 1.5$). Two guidelines (both classified as "To be discussed", $N > 4$) have been removed from the list. During the

Table 3
Relationships between the criteria used for the evaluation of the guideline's comprehensibility and related revision priority.

Criteria				Revision priority
N	C_M	SD_{CM}	Qualitative discussion	
$N \geq 5$	$C_M \geq 3.5$	$SD_{CM} \leq 1$	Not necessary for decision	Approved as it is
	$3.5 > C_M \geq 3$	$SD_{CM} \leq 1$	Necessary for decision	Minor revision
	$C_M \geq 3.5$	$1 > SD_{CM} \geq 1.5$	Necessary for decision	
	$3.5 > C_M \geq 3$	$1 > SD_{CM} \geq 1.5$	Necessary for decision	To be discussed (decide if "Minor revision" or "Major revision")
	$C_M < 3$	Irrelevant	Necessary for decision	Major revision
	Irrelevant	$SD_{CM} > 1.5$	Necessary for decision	
$N < 5$	Irrelevant	Irrelevant	Necessary for decision	To be discussed (decide if "Approved as it is ", or "Minor revision" or "Major revision")

Table 4
Example of how the guidelines have been revised according to their scores and selected cut-offs.

Nr	Guideline	Scores		Decision	Revised version of the Guideline
		C_M	SD_{CM}		
4	Provide functions of the workstation systems (including the robotic system) that adapt to the user's preferred working methods	3.9	0.7	Approved as it is	Not necessary.
1	Locate the robot system as distant as possible from the user's position according to the required level of interaction	3.2	0.9	Minor revisions	Locate the robot system at a comfortable distance from the user's position according to the required level of interaction.
30	Avoid the risk of misinterpretation of received or visualized information by the user (i.e., prevent potentially contradictory, conflicted or delayed information exchange)	2.9	1	Major revisions	Ensure that the information received by the user is clear and unambiguous (e.g., avoid potential contradictions, conflicts, or delays in the information exchange)

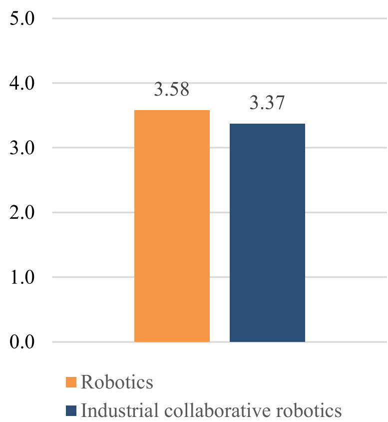

Fig. 3. Average expertise of respondents (according to a 5-Likert scale) about the general topics of robotics and industrial collaborative r obotics.

revision process and according to qualitative feedback, the research team decided to discard them due to (i) the impossibility of changing their contents without disrupting the guideline's structure and (ii) no solid scientific evidence to support the indications. Further details are provided in the next section.

4.2. Final list of revised guidelines

In the following, Table 5 summarizes the final list of the revised guidelines. These are organized through five categories (i.e., "Workstation and Robot System Features", "Robot System Performance and Interaction Patterns", "Human-Robot Communication and Interfaces", "Control Measures", and "Organizational Measures and Training"), which are used to group guidelines with similar objectives to better guide a designer focusing on specific parts of the collaborative application. In that regard, the authors suggest creating a group of designers

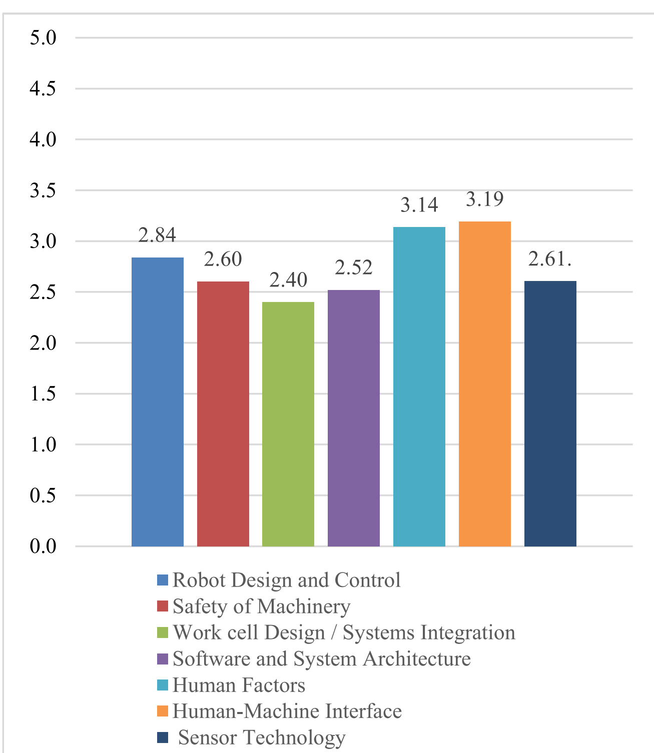

Fig. 4. Average expertise of respondents (according to a 5-Likert scale) about the main topics covered by the guidelines.

composed of experts in different disciplines. According to every expert's personal experience and skill, they can focus on the topics they are more familiar with by using the category as a general guide. Several experts and certification bodies widely use and suggest such a collaborative and interdisciplinary method to design safety-critical systems.

According to the qualitative feedback and after the final revision process, guidelines nr. 2 and 6 have been deleted for the above-mentioned reasons, while guideline nr. 15 has been divided into two to reduce its complexity and allow a better understanding.

Guideline nr. 2 was deleted for two main reasons. First, according to the qualitative feedback of the experts who assessed the guideline, it could conflict with other requirements in industrial environments. Some experts, in fact, stated that in manufacturing contexts, a high-contrast coloured robot concerning the workstation would be necessary to make it more conspicuous for workers in the vicinity. Secondly, there was a lack of strong scientific evidence supporting the effectiveness or necessity of employing workstation elements with reduced contrast about the robotic arm. The guideline was derived from a single conference proceeding paper (Schmidtler et al., 2015), and given the divergent opinions provided by the experts who participated in the survey, the researchers' team deemed the evidence backing the guideline too weak to be included in the final list.

Guideline nr. 6 was removed for similar reasons. There was significant disagreement among experts regarding the guideline's relevance and applicability. This discrepancy in experts' opinions is also reflected in a lack of consensus in the field about the most effective approach to designing the appearance of robotic systems in industrial settings. Such contrasting feedback indicates that the guideline may not universally apply or need more nuanced consideration depending on specific contexts or applications. Furthermore, the guideline was initially based on literature that, while relevant at its publication time, e.g., (Richert et al., 2016), has since become somewhat dated. More recent studies in the field have begun to provide evidence that contradicts these earlier findings, suggesting that some form of incorporation of anthropomorphic appearance and human-like features in robotic systems may have beneficial aspects in specific industrial applications (Roesler et al., 2021). This evolving landscape of research indicates that the guideline might no longer align with the most current understanding and best practices in the iHRI design.

4.3. Experts' opinions of guidelines impact

Additionally, Table 6 summarizes the experts' opinions on how guidelines affect safety, workers' well-being, and production performance. This has been collected through the survey by asking the following question: "*To what extent do you believe the implementation of*

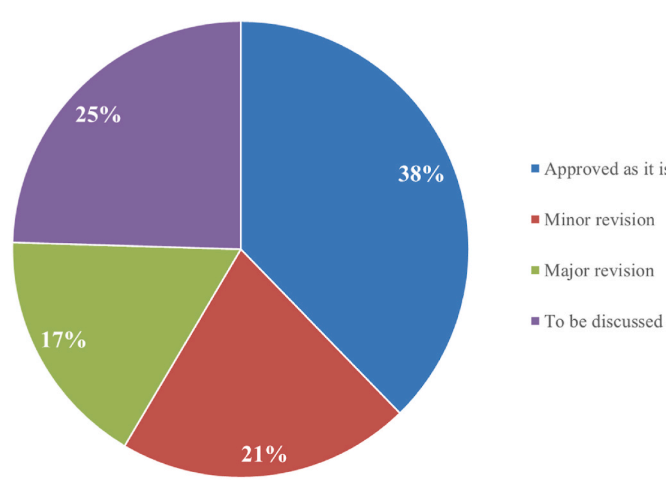

Fig. 5. Classification of the guidelines according to the revision priority.

Table 5
Revised guidelines final list.

Guideline Category	Nr	Guideline
Workstation and Robot System Features	1	Locate the robot system at a comfortable distance from the user's position according to the required level of interaction
	2	DELETED after the revision – the original form was: Design the visual appearance of the workstation using low-contrast workstation elements with respect to the robotic system
	3	Design workstation elements aligning user inputs with corresponding system outputs in a manner that reflects natural human behaviour (e.g., a left button press on an alarm on the left side of the screen)
	4	Provide functions of the workstation systems (including the robotic system) that adapt to the user's preferred working methods
	5	Realize a fluent and smooth aesthetic robotic system design (i.e., avoid bulky joints, wires, external arm components, and mechanized shape)
	6	DELETED after the revision – The original form was: Design the robotic system and related devices with industrial appearance (i.e., avoid adding social appearance and human-like features, e.g., anthropomorphism)
	7	Avoid similar types, colours, and appearance of multiple robotic systems that have to interact with the user (a group of similar robots can be seen as threatening)
Robot System Performance and Interaction Patterns	8	Provide measures for the adaptation of robotic system behaviour and interaction patterns to correspond with a user, considering the capabilities and skills of the user
	9	Make the robotic system able to understand, interpret and anticipate the user's actions, intentions and decisions like in human-human interactions (i.e. goal-oriented)
	10	Allow the robotic system to adapt its behaviour and communication mode considering previous interactions and works made in collaboration with the user (i.e., adaptability by learning)
	11	Design a consistent and coherent behaviour of the robot system that is comprehensible for the user (e.g., avoid supposedly arbitrary actions of the system)
	12	Avoid (frequent) variations in robot system velocity (by considering a slow velocity as a reference starting value)
	13	Avoid similar behaviour (e.g., movements, tasks, decisions) of multiple robotic systems that have to interact with the user (a group of similar robots can be seen as threatening)
	14	Ensure that the robotic system transfers objects to the user within the comfortable reach zone
	15	15a: Enable the robotic system to foresee user's intentions to physically interact with it and deal with their intended actions in advance 15b: Enable the robotic system to disregard the user's unintended actions that may mistakenly trigger a response (false positive actions).
	16	Plan the actions of both the user and robotic system to avoid conflicts (e.g., motions that can lead to collisions, actions that can lead to misunderstandings, etc.)
	17	Adopt user-centred approaches to design pleasant interaction patterns and corresponding human-machine interfaces (e.g., through usability methods based on focus groups, thinking aloud, questionnaires, and expert evaluation)
	18	Prevent the communication of an erroneous intent by the robotic system through the use of social conventions (e.g., handing over a screwdriver by offering its handle)
Human-Robot Communication and Interfaces	19	Support users and robotic systems to share the same communication model (e.g., language) and use vocabulary that is simple and easy to understand
	20	Suggest adequate work breaks to improve user's performance and concentration
	21	Make the robotic system request interactions without distracting or interfering with the user's motor activities, attention and comprehension
	22	Make the user intuitively and immediately aware of the robotic system status, behaviour (e.g., movements, tasks, decisions) and intentions when relevant and necessary
	23	Personalize information amount, form, content, and communication mode considering user's interaction preferences
	24	Allow the user to provide feedback to the robotic system to confirm or reject a proposed action plan if needed
	25	Provide measures that allow the robotic system to explain its decisions to the user when necessary and applicable
	26	Inform the user about the type and functioning of specific safety measures used during the interaction
	27	Design the interfaces (i.e., notification modality/format/timing) to support the user in easily and unambiguously understanding the information
	28	Make the robotic system able to communicate apology statements (i.e., acknowledge errors and take responsibility) in case of errors or mistakes
	29	Simplify robot-to-user communication by avoiding sending unnecessary and overly complex information
	30	Ensure that the information received by the user is clear and unambiguous (e.g., avoid potential contradictions, conflicts, or delays in the information exchange)
	31	Provide multimodal (e.g., visual, auditory, haptic) and complementary communication channels in a redundant way
	32	Provide measures to communicate with the user without losing focus on the task (e.g., transfer the graphic user interface onto the collaborative workspace or design on-board devices for visual communication)
	33	Allow the user to understand a forthcoming task in advance (e.g. by using preparatory notifications)
	34	Allow the user to intuitively understand beforehand the intentions of the robotic system, the spatial occupancy of its planned motions and signal its target and interested workpieces
Control Measures	35	Make the control of the user on the robotic system as natural, intuitive and explicit as possible
	36	Provide workstation systems (including the robotic system) that adapt safety strategies to the user's preferences
	37	Design the robotic system to value the expertise and skills of the operators (e.g., employ her/his competences properly)
	38	Allow the user to provide real-time corrections to key arbitrary robotic system's state and in case of disagreement with its autonomous behavior
	39	Allow the user to set the preferred level of autonomy of the robotic system (by considering a medium level as a reference starting value)
Organizational Measures and Training	40	Demonstrate to the user the effectiveness and reliability of safety measures of the robotic system prior to starting the interaction
	41	Demonstrate to the user the efficiency and reliability of the robotic system elements prior to start the interaction (e.g., show the capability of the end-effector to firmly hold a workpiece during the whole task)
	42	Make the robotic system perceived by the user as a useful, effective and reliable workmate (and not only as a tool) instead of a competitive entity
	43	Use common language and human-like terminology when presenting the robotic system to the users and terminology that highlights its cooperativeness

(*continued on next page*)

Table 5 (*continued*)

Guideline Category	Nr	Guideline
	44	Engage operators in workstation, interface, interaction, job sequence design and evaluation following an iterative process and including a multidisciplinary design team
	45	Provide training and empowerment to the user when designing, implementing and working in the workstation (e.g., understand the abilities and limitations of the robotic system, tasks complexity, and the underlying causes contributing to events)
	46	Support the user to discover purpose and fulfilment in their work, take ownership and responsibility for their work outcomes, and gain a clear understanding of the impact of their efforts
	47	Establish a "process champion" who agrees with the technology implementation and can cascade this knowledge to the rest of the team
	48	Enable user's positive initial experiences with the robotic system during the early interaction period to prevent disuses or misuses
	49	Support users without prior experience in interacting with robots to understand the abilities and limitations of the robotic system and compare them to their own
	50	Support the management to clearly communicate intents, rationale, goals and effects related to the introduction of the collaborative robotic system as well as their I and support to the changes
	51	Consider users' and stakeholders' inputs during the hazard identification, risk assessment and safety measures validation
	52	Ensure the user's agency (i.e., the capacity to take informed decisions and actions independently), sense of control and responsibility over the work when delegating decisions and tasks to the robotic system
	53	Implement measures to counteract deskilling of operators when possible and appropriate

this specific Guideline will have an impact on the following aspects (safety, worker's well-being, production performance)?" and collecting the answers by using a 5-points Likert ranking scale.

These results will further help the designers to understand the most impactful guidelines better, thanks to the experts' responses, and, therefore, suggest a priority of implementation. Nevertheless, the authors want to underline that the presented general classification should be carefully evaluated by considering different aspects of the collaborative application, such as the required level of iHRI, the main process features, the environmental and organizational conditions, etc. (see the discussion section for further details). In that regard, Table 7 summarizes the most impactful guidelines according to the above data. Similar to what is proposed for the definition of the criteria of Table 3, the most impactful guidelines were defined as those with the following values: $M_I \geq 3.5$ and $SD_I \leq 1$.

5. Discussion

5.1. Theoretical implications

According to the vision of the authors, iHRIs in Industry 5.0 settings will be based on human-centred robotic systems able to operate in unstructured working environments and to rearrange their operations instantaneously, semi-independently, and according to the worker's requirements (i.e., needs and wants). In that regard, the guidelines (especially the ones belonging to the categories "Robot System Performance and Interaction Patterns", "Human-Robot Communication and Interfaces", and "Control Measures") support the implementation of adaptive behaviour of the robotic systems. In particular, such adaptability should be (i) automatic (i.e., working by itself with little or no direct human control, when possible and useful), (ii) seamless (i.e., smooth and continuous, without any sudden changes, interruption, or difficulty), (iii) dynamic (i.e., continuously changing or developing according to the evolution of the situations), and (iv) quasi-real time (i.e., processed so that feedback is virtually immediately available to the human). This will take cyber-physical and human-centred production systems to the next level while introducing several important opportunities, challenges, and threats from a human perspective. Therefore, the "limited" approach of managing iHRIs by focusing on the sole minimization of mechanical risks introduced by the sharing of workspaces and activities must be overcome. In this regard, the authors emphasize that an interdisciplinary team developed the guidelines to support the next generation of designers in preventing emerging sociotechnical risks associated with advanced industrial robotics. This study differs from the previous one (Gualtieri et al., 2022) from (i) the methodological approach and (ii) the context.

Considering the former point, this work foresees a more structured way to develop and update the guidelines and validation based on an extensive expert survey (these parts were not included in the previous study). While other studies used similar methodologies in other fields and different topics (Miesbauer and Weinreich, 2013; Kwok et al., 2023; Yang et al., 2020; Sobrino-García, 2021), this study is the first to improve, revise, and submit to experts' judgment guidelines for enhancing cognitive ergonomics in iHRI. Expert feedback helps validate the guidelines and ensures their effectiveness in improving cognitive ergonomics in iHRI, following recommendations stemming from previous research (Hopko et al., 2022). Experts' profound knowledge and experience in iHRI gave us a comprehensive and accurate evaluation of the revised guidelines and assured us that they align with contemporary research and best practices. In this process, experts gave feedback on the guidelines' comprehensibility and practicality, which have been used to refine and enrich the set of proposed items. Furthermore, incorporating experts from various disciplines allowed for a multifaceted evaluation, ensuring the guidelines are well-rounded and robust by considering multiple perspectives. Expert evaluations are also fundamental for quality assurance. They helped to identify potential gaps, inconsistencies, or shortcomings in the guidelines, thus ensuring their reliability and trustworthiness. Engaging experts in the evaluation process has made the guidelines more rigorous, evidence-based, and practical for real-world scenarios. This involvement bolsters credibility and enhances the overall quality of the guidelines, making them highly beneficial for practitioners and non-experts alike.

Regarding the latter point, this study refers to iHRIs within Industry 5,0, which encompasses advanced (i.e., intelligent and adaptable) robots, while the previous one referred mostly to 6-degrees-of-freedom fixed collaborative arms working in a static workstation, a typical example of collaborative application in Industry 4.0. In fact, updated guidelines have been defined universally and flexibly so that they can be used to design a broader range of human-centric applications, e.g., using "traditional" industrial robots, cobots, mobile robots, industrial humanoids, etc. This allows the prevention of future scenarios that have not been investigated from a human-factors perspective by further emphasizing the role of the guidelines in social sustainability in the face of Industry 5.0 development.

5.2. Importance for the industry

The guidelines proposed in this paper will help improve worker safety, ergonomics, wellbeing, and production performance. Substantial evidence exists in the scientific literature that improving working conditions can lead to higher job satisfaction and, at the same time, reduced absenteeism, injuries, and occupational illnesses. In many industrial sectors (e.g., manufacturing), improved ergonomics and well-being reflect better working conditions for operators and, thus, higher

Table 6
Experts' opinions of guidelines affect safety, well-being, and production performance. M_I and SD_I are the assessed impact's mean value and standard deviation.

Guideline Category	Guideline	Impact					
		Safety		Worker's well-being		Production Performance	
		M_I	SD_I	M_I	SD_I	M_I	SD_I
Workstation and Robot System Features	1	4.22	0.972	2.56	0.882	2.44	1.130
	2	3.13	1.458	3.00	0.926	2.50	1.512
	3	2.71	1.254	3.29	1.113	3.57	0.787
	4	3.80	0.632	4.40	0.966	4.20	0.919
	5	3.91	1.136	3.55	0.934	2.91	1.300
	6	2.67	1.366	2.33	1.506	2.67	1.033
	7	2.70	1.567	2.80	1.476	2.40	1.430
Robot System Performance and Interaction Patterns	8	4.11	0.782	4.22	0.833	3.56	1.014
	9	4.25	0.886	4.25	0.707	2.75	1.035
	10	4.00	1.195	4.00	0.926	4.13	1.246
	11	4.09	0.944	4.27	0.905	4.00	1.095
	12	4.00	0.577	3.86	0.690	3.71	1.254
	13	2.70	1.337	2.70	0.949	2.60	0.966
	14	3.55	1.036	4.09	0.701	3.64	1.027
	15	2.67	1.211	2.67	1.366	2.50	0.837
	16	4.00	1.612	3.18	1.401	3.00	1.183
	17	3.44	0.882	4.00	0.707	3.44	1.130
	18	5.00	0.000	4.75	0.500	4.75	0.500
Human-Robot Communication and Interfaces	19	3.83	0.753	4.00	0.632	3.67	0.816
	20	3.83	0.937	3.92	0.996	3.75	0.965
	21	3.67	0.866	3.56	1.130	3.67	0.707
	22	4.20	0.789	4.00	0.816	3.60	0.699
	23	3.38	1.408	3.75	1.165	3.25	1.389
	24	3.50	1.269	3.70	1.252	4.00	0.816
	25	3.83	0.753	3.83	1.169	3.17	0.753
	26	3.60	0.548	3.80	0.837	3.60	0.548
	27	3.67	0.866	3.89	1.054	3.78	0.972
	28	2.80	1.317	4.00	0.667	2.80	0.919
	29	2.89	1.453	3.67	1.414	3.33	1.414
	30	4.00	0.471	3.70	0.949	3.50	0.707
	31	3.50	0.577	3.25	0.500	3.25	0.500
	32	3.50	1.269	3.80	0.919	3.80	0.919
	33	3.63	1.188	3.88	0.991	3.88	0.641
	34	3.89	0.928	4.00	0.866	2.89	0.928
Control Measures	35	3.67	0.866	3.67	1.118	3.67	0.866
	36	4.10	0.994	3.80	1.033	3.10	1.370
	37	3.30	1.418	4.10	0.994	3.80	1.135
	38	4.25	1.389	4.13	0.835	3.63	0.916
	39	3.50	1.378	3.00	1.414	3.50	0.837
Organizational Measures and Training	40	4.70	0.483	4.10	0.738	3.80	0.422
	41	3.92	0.996	3.83	0.835	3.58	1.165
	42	2.73	1.191	3.73	1.104	3.82	0.874
	43	3.11	1.167	3.44	1.130	2.89	0.782
	44	2.73	1.191	3.64	1.120	3.45	1.368
	45	3.29	1.604	3.00	1.414	2.71	1.380
	46	3.17	1.169	4.17	1.169	4.17	1.169
	47	2.50	1.291	2.50	1.291	3.25	1.500
	48	3.67	1.033	3.67	1.211	3.50	1.049
	49	2.57	1.718	2.71	1.113	3.14	1.345
	50	2.71	1.254	3.57	1.512	3.57	1.272
	51	4.50	0.837	4.17	0.753	3.33	1.366
	52	3.17	1.030	3.33	0.888	3.17	0.835
	53	3.38	0.916	3.75	0.707	3.13	1.126

company performance (Zare et al., 2016) and productivity (Vink et al., 2006). In addition, the proper use of cobots can also positively affect product (El Makrini et al., 2019) and process quality as well as efficiency (Weckenborg et al., 2020) by improving the overall production performance (Fraune et al., 2022). These aspects are of utmost importance in modern industrial contexts where (i) production is characterized by the need to balance productivity and flexibility, and (ii) there may be multiple variants of the manufactured product (i.e., mass customization).

Furthermore, more ergonomic applications also mean easier and wider technology adoption in production processes. In this regard, the guidelines also aim to achieve a tangible and measurable impact in the following areas: (i) robot development, design, and integration – helping designers identify the best robot interfaces, features, and interaction patterns to achieve an optimal level of iHRI; (ii) use of robotics/automation in industrial production – improving the usability and reconfigurability of collaborative applications, paying particular attention to user needs and wants to ensure the ability to adapt to continuous market changes.

All these potential achievements align with the overall objectives of Industry 5.0 regarding social and economic sustainability.

5.3. Importance of standardization bodies

According to recent studies by the European Agency for Safety and Health at Work (https://osha.europa.eu/en/publications/future-work-

Table 7
Most impactful guidelines categorized according to the impact area and category.

Guideline Category	Guidelines number			
	Safety	Workers well-being	Production Performance	Relevance for all the areas
Workstation and Robot System Features	1, 4	4, 5	3, 4	4
Robot System Performance and Interaction Patterns	8, 9, 11, 12, 18	8, 9, 10, 11, 12, 14, 17, 18	18	18
Human-Robot Communication and Interfaces	19, 20, 21, 22, 25, 26, 27, 30, 34	19, 20, 22, 26, 28, 30, 32, 33, 34	19, 20, 21, 22, 24, 26, 27, 30, 32, 33	19, 20, 22, 26, 30,
Control Measures	35, 36	37, 38	35, 38, 39	/
Organizational Measures and Training	40, 41, 51	40, 41, 51, 53	40, 42	40

robotics), iHRI will provide several benefits and challenges soon. One of the key points will be the study of technology management and user experience. Most people do not have experience interacting with robots, but this is set to change as human-machine interaction increases in the workplace. The effects of robotics on worker safety and well-being are not widely understood. For these reasons, psychosocial factors associated with intelligent robotics will also require more occupational health and safety attention. Except for the recent ISO/TR 9241-810 (International Organization for Standardization, 2020) (which does not specifically address industrial cobots), to the extent of our current understanding, there is no technical documentation (i.e., deliverables and standards) for cognitive ergonomics in iHRI. Creating knowledge (e.g., the proposed guidelines) on iHRI considering different robot performances and workstation features in multiple work conditions will consistently contribute to the diffusion of human-centred, safe, and sustainable collaborative applications. This will contribute to the ongoing progress of extensive technical documentation across Europe focusing on the psychosocial requirements for advanced industrial collaborative applications.

5.4. Relevance of the guidelines in terms of resilience in manufacturing systems

The relationship between resilience in manufacturing, human-centred design, and the improvement of HF&CE in iHRI is essential in Industry 4.0/5.0. Human-centred design and cognitive ergonomics are critical factors in ensuring workers' safeguarding and efficiency in manufacturing (Reiman et al., 2021; Boschetti et al., 2022). In iHRI, the focus is on designing robots that can collaboratively work alongside humans to improve productivity and human reliability, and this requires careful consideration of factors such as safety measures based on power and force limiting, as well as monitoring operator fatigue and intention and designing safe human-robot collaborative workplaces (Matheson et al., 2019). By improving the ergonomics of work systems and designing robots that can work safely alongside humans, manufacturers can improve the resilience of their operations and reduce the risk of disruptions due to worker injury or error. Indeed, resilience and adaptability in manufacturing are increasingly recognized as a direct reflection of robust, intelligently designed iHRIs (Reiman et al., 2021). Addressing cognitive ergonomics specifically implies understanding the mental demands, decision-making processes, and allocating attention in a human-robot collaborative environment. Industry 5.0, highlighting the cooperation between humans and machines, further necessitates this focus on cognitive ergonomics to foster a work culture that is physically safe, mentally stimulating, and devoid of cognitive strain, leading to fewer errors and better problem-solving. The concept of resilience in this context extends beyond the immediate ability of an operation to recover from disturbances, and it incorporates the long-term ability of the system to adapt to changes, learn from mistakes and continuously improve. Such adaptability is contingent on the depth of advanced iHRI and the level of mutual understanding and learning between the two entities. By considering HF&CE, iHRIs can be designed to learn from and adapt to human operators in a symbiotic way, enhancing both the resilience of production tasks and the well-being and productivity of workers. Furthermore, addressing human factors in iHRI design extends to acknowledging human operators' diversity in terms of their cognitive capabilities, learning styles, and physical attributes. Consequently, customized and adaptive systems can support a broader demographic of workers, bolstering overall operational resilience. This inclusivity allows the absorption of a wider range of skills and perspectives, fostering innovative problem-solving and adaptability and further strengthening the resilience of industrial operations in an ever-evolving, competitive market.

In the following, Table 8 summarizes the relationship between the proposed guidelines and the main requirements for the development of a resilient cyber-physical manufacturing system. Such requirements have been derived from the scientific literature by analyzing and summarizing the features discussed by Hosseini et al. (2016), Komesker et al. (2022), Fowler et al. (2023), and Disconzi and Saurin, 2022, 2024. It is evident how the application of the guidelines can significantly contribute to meeting the requirements, especially considering a human-factors perspective. In particular, the technical and organizational requirements that are mostly addressed are the ones related to the system's reconfigurability, flexibility, and adaptability, as well as the ones related to the implementation of safe, robust, and redundant applications. In that regard, the support for designing adaptable and autonomous iHRIs, multimodal human-machine interfaces, seamless communication, and the empowerment and involvement of workers and management are the most impactful contributions of the guidelines.

The results and considerations of the present study allow us to explicitly address the Research Questions (RQ) proposed in the introduction. In addressing RQ1, we emphasize the criticality of three core principles: managing cognitive load to balance information processing demands, ensuring natural and intuitive iHRIs, and designing ergonomic collaborative applications that facilitate physical and cognitive efforts. Our results suggest that these fundamental ideas highlight the critical role that HF&CE plays in designing collaborative human-robot systems and are necessary to improve their effectiveness and safety. In response to RQ2, our developed guidelines adeptly bridge the gap for non-experts in integrating human-centred design principles into HRIs. These guidelines are crafted to focus on user-friendliness and accessibility, ensuring that individuals without extensive expertise in cognitive ergonomics can effectively apply them in industrial contexts. These recommendations simplify the intricacies of human-centred design by emphasizing practicality and ease of application. This hopefully facilitates the more seamless and effective integration of HRIs in industrial settings. Regarding RQ3, the present work effectively incorporates multidisciplinary expert feedback in the development of guidelines, enhancing their validity and applicability. The guidelines have been refined by engaging international experts from diverse fields such as industrial engineering, robotics, machinery safety, and human factors/ergonomics to address a wide range of perspectives and requirements. This collaborative approach ensures that the guidelines are comprehensive and practical for diverse industrial applications. Addressing RQ4, the guidelines contribute significantly to social sustainability and resilience in manufacturing environments. They facilitate the creation of more

Table 8
Contribution of the proposed guidelines to fulfil the requirements for developing a resilient cyber-physical manufacturing system (derived from (Hosseini et al., 2016; Komesker et al., 2022; Fowler et al., 2023; Disconzi and Saurin, 2024; Disconzi and Saurin, 2022)).

Requirements for resilience	Description	Related Guidelines
Modularize the system by using functional models	Design a modular product, process, and resource structure to enhance coordination and adaptability (considering multiple configurations). The operation should be modelled, indicating a comprehensive understanding of its functionality (i.e., explicitly).	1, 3, 4, 5, 7, 23, 31
Ensure understandable autonomy	Implement autonomy through adaptability (of a certain configuration), reconfiguration, monitoring, and reasoning for dealing with unforeseen changes. Highlight performance variability in real-time (i.e., support visibility).	8, 9, 10, 15a, 22, 23, 26, 27, 30, 31, 36,38
Prioritize scalability	Build scalability into the system to meet varying demands flexibly and maintain performance.	14, 24, 35, 39, 44
Embrace interoperability	Ensure that the system is interoperable, supporting seamless communication and information exchange.	11, 17, 18, 19, 21, 22, 25, 27, 29, 32, 33, 34, 43
Ensure smart standardization	Employ a form of standardization that aligns with the specific functionality of the system.	3, 12, 19, 31, 43
Incorporate recursiveness	Enable global planning and local control for effective coordination in both central and decentral systems.	13
Integrate resilience features	Incorporate resilience features like reliability, redundancy, reciprocity and robustness to enhance system resilience.	37, 41, 42, 46, 49
Address safety and security	Address physical and cybersecurity concerns to ensure the system's safety and security.	12, 16, 20, 26, 40, 48, 51
Enhance absorptive capacity	Develop mechanisms for absorbing shocks through protection, backup options, diversification and slack resources. Ensure satisfactory performance even in non-nominal situations.	15b, 18, 31, 45, 47, 52
Establish restorative capacity	Develop permanent solutions to restore disrupted components, ensuring a return to a steady state after disturbances.	28, 53
Employ a multi-perspective design approach	Design systems by considering a range of viewpoints in the decision-making process.	37, 44, 51
Employ continuous learning by design	Supporting continuous individual and organisational learning by considering it as a design requirement.	40, 41, 45, 46, 49

adaptive, human-centric workspaces, thereby enhancing the well-being and productivity of workers. This human-centred approach optimises efficiency and fosters a safer, more inclusive, and sustainable industrial ecosystem, aligning with the broader objectives of social sustainability in Industry 5.0.

5.5. Limitations and future work

One relevant limitation of this study is that the number of participants is small (to be enlarged in future studies). In addition, the authors understand that implementing a guideline can conflict with others, possibly leading to an adverse effect from the cognitive or safety perspective. This potential contrast should be further studied according to specific collaborative applications and working contexts. As an example, the implementation of Guidelines 11 and/or 12 may require "human-like" trajectories (e.g., minimum-jerk type (Rojas et al., 2022; Rojas and Vidoni, 2021)) to enhance cognitive variables such as human trust in robots. On the other hand, this trajectory can affect the operating workspace of the robotic system by potentially enlarging it if compared with a traditional trapezoidal speed profile. This may involve new mechanical risks (e.g., by increasing the probability of contract or entrapment) to be properly assessed and reduced.

Additionally, a random assignment was used to distribute five out of 53 guidelines to each participant for assessment of comprehensibility. The intention was to achieve an approximately equal distribution of participants across the guidelines, ensuring that an equal number of participants would evaluate each guideline. However, a relatively high dropout rate occurred (probably due to the questionnaire length and relatively high number of items with an open response format), resulting in an unequal distribution of respondents per design guideline. This uneven distribution may have introduced a potential bias in the evaluation of the guidelines. Another limitation of the study constitutes the diverse expertise of survey respondents and its alignment with the content of the guidelines. While the participants' professional backgrounds encompassed various fields, the nature of the random assignment of design guidelines did not allow to control that participants' expertise aligned with the content of the guidelines they assessed. However, this limitation can also be advantageous for the final aim of the design guidelines, as their objective is to support non-experts in HF&CE, ensuring that they are understandable not only to experts within the specific field of each guideline but also to experts from other disciplines.

It may be argued that the proposed guidelines are too general and do not indicate "how" to achieve the proposed goals. Nevertheless, since it is virtually impossible to forecast future technical and technological advancements, this approach is frequently applied in the context of safety-critical systems. In fact, the Machinery Directive (2006), which is the legal act of the European Union that sets out the health and safety requirements for the Member States with regard to the use of machinery, defines the results to be achieved or the risks to be avoided but does not specify or provide corresponding technical solutions. The same also applies to other relevant standards (e.g., ISO/TR 9241–810:2020 (International Organization for Standardization, 2020)). In general, it is the designer's responsibility to investigate or develop possible measures according to the state of the art. In this paper, the authors voluntarily take the same approach: the guidelines present the goal to be achieved by design without explaining the measures to implement or the positive effects that the guidelines may bring regarding human cognitive response.

Nevertheless, more technical support for designers is envisioned for the future. In that regard, the proposed guidelines are intended to be the core part of a "toolkit" (yet to be developed) to support non-expert designers and system integrators in developing practical solutions for essential cognitive needs in advanced collaborative applications. Toolkits, especially in the form of training units and modules, have been proven to support training individuals studying diverse Industry 4.0 concepts and technologies effectively (Bonello et al., 2022). The proposed toolkit will extend the information provided by the guidelines, adding related use cases and examples of implementation, best practices, suggestions for technical solutions, and methodologies for evaluating and monitoring main cognitive variables. A digital tool (e.g., software) could be very useful to support final users using the guidelines and related toolkit properly. Furthermore, an experimental validation that involves designers (in a virtual environment or a quasi-realistic industrial context) will be considered to further test the potential of the guidelines/toolkit.

The expert survey also collected qualitative suggestions about possible practical solutions for the guideline's implementation and Key Performance Indicators (KPIs) for results evaluation. Such information will be used to identify the most impactful design factors affecting iHRI from a cognitive perspective. This structured analysis will be discussed in future works. Furthermore, an assessment method for quantifying the effectiveness of implementing the guidelines and related technical solutions is necessary. Such a method should identify and quantify the relationships between the features of the collaborative application (e.g., robot system features and performances, workstation layout and elements, iHRI patterns, organizational measures, etc.) and the main cognitive variables related to the operator's safety, ergonomics and well-being, e.g. the cognitive workload. In that regard, a method for evaluating the cognitive workload that specifically refers to iHRI should be included in the abovementioned toolkit. This can be inspired by the so-called "Cognitive Load Assessment Method" (CLAM) (Thorvald et al., 2017b) and considers the unique characteristics of industrial cobots.

6. Conclusions

This study presents a structured process for developing and validating guidelines aimed at supporting non-experts in the field of HF&CE (e.g., industrial engineers, roboticists and system integrators) in the design of human-centred and collaborative production systems. These guidelines were developed by an interdisciplinary team of researchers with expertise in industrial engineering and occupational psychology who have prior experience in this area. The main phases for developing, revising, updating, and validating the guidelines were defined and discussed. A survey was developed to explore in depth how international experts in different disciplines (i.e., industrial engineering, robotics, safety of machinery, human factors/ergonomics, or work and organizational psychology) interpret and assess the guidelines. Participants (n = 108) were asked to rate the guideline's comprehensibility and usefulness through items on a 5-point Likert rating scale. As a result, the guidelines have been classified: 38% as understandable (no revisions were required), 21% as not totally understandable (minor revisions were required), and 17% as deficient (major revisions were required). Based on the survey outcomes, the guidelines were revised using quantitative data (number of respondents, mean comprehensibility scores, associated standard deviation) and qualitative data (feedback from open-ended questions) and written in its final form. In particular, a revision hierarchy that allows the understanding of the number, importance, and type of changes required has been proposed. It is based on the combination of the numbers of respondents (*N*), as well as the mean comprehensibility values (C_M) and related standard deviation (SD_{CM}) of their feedback.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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