Development and evaluation of design guidelines for cognitive ergonomics in human-robot collaborative assembly systems

Development and Evaluation of Design Guidelines for Cognitive Ergonomics in Human-Robot Collaborative Assembly Systems

Luca Gualtieri[1], Federico Fraboni[2], Matteo De Marchi[1], Erwin Rauch[1]*

[1]Industrial Engineering and Automation (IEA), Faculty of Science and Technology, Free University of Bolzano, Piazza Università 5, 39100 Bolzano, Italy

[2]Department of Psychology, Università di Bologna, Via Zamboni 33, 40126 Bologna, Italy

* Corresponding author: Tel.: +39-0471-017111; E-mail address: erwin.rauch@unibz.it

Abstract:

Industry 4.0 is the concept used to summarise the ongoing fourth industrial revolution, which is profoundly changing the manufacturing systems and business models all over the world. Collaborative robotics is one of the most promising technologies of Industry 4.0. Human-robot interaction and human-robot collaboration will be crucial for enhancing the operator's work conditions and production performance. In this regard, this enabling technology opens new possibilities but also new challenges. There is no doubt that safety is of primary importance when humans and robots interact in industrial settings. Nevertheless, human factors and cognitive ergonomics (i.e. cognitive workload, usability, trust, acceptance, stress, frustration, perceived enjoyment) are crucial, even if they are often underestimated or ignored. Therefore, this work refers to cognitive ergonomics in the design of human-robot collaborative assembly systems. A set of design guidelines has been developed according to the analysis of the scientific literature. Their effectiveness has been evaluated through multiple experiments based on a laboratory case study where different participants interacted with a low-payload collaborative robotic system for the joint assembly of a manufacturing product. The main assumption to be tested is that it is possible to improve the operator's experience and efficiency by manipulating the system features and interaction patterns according to the proposed design guidelines. Results confirmed that participants improved their cognitive response to human-robot interaction as well as the assembly performance with the enhancement of workstation features and interaction conditions by implementing an increasing number of guidelines.

Keywords: collaborative robotics, collaborative assembly systems, cognitive ergonomics, human factors, industry 4.0.

1. Introduction

a. Problem statement

New technological advancements are shaping the current transition of many organizations towards the concept of Industry 4.0, which has been typified by new levels of sociotechnical interaction between different manufacturing assets across the supply chain [1]. Previous authors connected Industry 4.0 to advanced digital technologies such as Autonomous and Collaborative Robots [1, 2]. The International Federation of Robotics (IFR) defines industrial collaborative robots as those able to perform tasks in collaboration with workers in industrial settings [3]. Industrial Human-Robot Interaction (HRI) aims at improving both operator's work conditions and production performance by bringing together the individual agent contributing strengths (e.g. humans' versatility and dexterity with robots' speed and accuracy), which compensate for the weaknesses of the other, rather than negating the need for one agent or the other [4]. Collaborative robotic arms and related integrated devices (e.g. collaborative end-effectors) present hardware and software solutions that allow the implementation of a collaborative robotic system[1] and, as a consequence, a "collaborative application". The greatest innovation with respect to "traditional" industrial robotics is related to the possibility for the operator to voluntarily (functional interaction, i.e planned action) or involuntarily (non-functional interaction, i.e unexpected/unwanted contact) interact with the robotic system under certain controlled conditions that have to be carefully evaluated through a risk assessment [5]. This allows the operator to interact with the robotic system physically, flexibly, and safely, without the need to isolate tasks and workspaces due to safety reasons (e.g. by using safety fences) [6].

HRI can generally be considered the broad category of actions that can determine mutual or reciprocal influence between humans and robots. Communication, cooperation and collaboration between humans and robots can be considered sub-categories of HRI [7]. Human-robot collaboration (HRC) can be considered the most advanced implementation of HRI in the industry. While HRC has been generally referred to as the use of industrial robotic systems without safety fencing [8], authors argued that HRC should be described as a series of joint actions towards a common goal, in which operators and robotic systems work simultaneously on the same product or component by adapting to each other [9].

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[1] Note that in this work a "robotic system" is defined as the integrated system composed by the robot (arm), the controller, the end-effector and possible related devices (e.g. sensors) needed to properly perform production tasks.

Industrial HRI introduces multiple advantages but also challenges [6]. In this regard, one of the most interesting and challenging applications is product assembly. This is a very promising way to make production more flexible and agile by responding to the ever more demanding requirements of Industry 4.0. Collaborative Assembly Systems (CASs) are a real example of semi-automated and human-centered manufacturing systems where operators and machines interact for the assembly of manufacturing products. CASs entails new forms of interaction between humans and automation and profound changes in work both at the operational level and in its nature [1]. Those changes also imply human factors and ergonomics-related challenges and risk factors such as stress and burnout [10], information overload [11], workers' safety [12], increasing cognitive load [13], frustration and loss of motivation [14]. Previous authors, addressing cognitive risk factors in work environments, highlighted that excessive levels of cognitive workload, as well as low usability, entails risks to workers' performance and wellbeing [15]. In fact, excessive cognitive demands in work environments can lead to cognitive failures that affect overall performance [15]. These risks, related to the design of work tasks, technologies and environments may have a detrimental impact on both the mental and physical health of employees [16]. In that regard, themes like trust [17,18], acceptability [19], and human-robot teaming [20, 21], have been preliminarily studied in the field of social and industrial HRI.

Previous research thus shows that cognitively straining conditions can have direct effects on task performance, as well as indirect, extensive effects on work performance and productivity if they expose employees to cognitive failure and impair occupational safety and health. Occupational safety is widely perceived as of primary importance when humans and robotic systems have to work together in industrial settings [22]. On the other hand, human factors and cognitive ergonomics are often underestimated or ignored when designing and implementing HRIs and therefore CASs, even if they are crucial for the operator's wellbeing and production performances [10]. These issues have been little considered even in academia until recently [6]. Human factors and ergonomics are fundamental in the design of high-tech, automated and, complex systems (e.g. robotic systems), since they are strictly related to the operator's safety, wellbeing, and work-related performance [25].

The present work thus focuses on cognitive ergonomics in industrial HRI. It refers to the development and experimental evaluation of a set of design guidelines related to cognitive

ergonomics in CASs. These have been identified by systematically analyzing the scientific literature. A laboratory case study has been used for the evaluation of such guidelines.

In industrial engineering, one of the main tools for helping designers in the fulfillment of design requirements is represented by technical standards and deliverables [26]. These include guidelines and indications on how to realize effective and state of the art solutions (e.g. products, systems, services, etc.). At the moment, deliverables (e.g. standards) and related guidelines for the design of human-centered and cognitive-oriented industrial systems based on HRI (e.g. CASs) are missing.

In that regard, the present paper ultimately aims to provide suggestions and recommendations, in the form of guidelines, for technicians to consider human factors and operators' cognitive ergonomics when designing and implementing CASs. The guidelines shown in the present work can be a starting point for future research and investigation related to human factors and ergonomics aspects in collaborative robotics. Neglecting cognitive ergonomics when designing CASs may involve various risks for the operator and lead to a considerable worsening of working conditions [10-16], as mentioned earlier. In addition, addressing cognitive aspects, such as task allocation, could increase the system's overall efficiency and significantly improve potential returns for investing in collaborative robotic technology [27]. With that said, the target audience will be mainly composed of (i) industrial designers and systems integrators (with no/limited expertise in human factors but expertise in manufacturing/robotics), (ii) researchers interested in the topic and, (iii) policy-makers bodies (e.g. EUOSHA or ISO).

The article is structured as follows. Section 1 provides the problem statement according to the review of the scientific literature and explains the process for the development of the guidelines. Section 2 describes the guidelines as well as the materials and methods adopted for their experimental evaluation. Section 3 summarises the main qualitative and quantitative results. Finally, the discussions and conclusions are summarised in Section 4 and Section 5, respectively.

b. Guidelines development

The study of cognitive ergonomics in the field of industrial collaborative robotics is still in its infancy. After preliminary studies on the topic [22-24], the guidelines' content was identified based on a detailed analysis of the scientific literature. This was performed in spring 2020 according to a systematic approach. Scopus was used as the electronic database for keywords

search. The authors identified it as being the most relevant for publications in the area of collaborative robotics. A previous control of other sources such as ISI Web of Knowledge, Emerald, and Science Direct did not show any major changes in relation to adding to the sources. The keywords used in this analysis were identified by preliminarily reading different articles on the topic related to the role of cognitive ergonomics in industrial HRI. In particular, to make the research as complete as possible, the following research keywords have been used: "ergonomics" OR "ergonomic" OR "human factors" OR "human-factors" OR "cognitive ergonomics" OR "psychological risk" OR "psychological" OR "work stress" OR "work-related stress") AND ("Collaborative Robotics" OR "Human Robot" OR "Collaborative Robot" OR "Human Robot" OR "CoBots" OR "Human-Robot" OR "HRI" OR "HRC") AND ("industrial" OR "industry"). In addition, the following constraints were applied: "article title/abstract/keywords" as search fields, "final" as publication stage, "English only" as language and "≥ 2011" as time-period. The year 2011 was selected since it represents the beginning of the Industry 4.0 era. Besides, considering the novelty of the topic, the author considered this period as large enough for this analysis.

This search resulted in 140 documents. To ensure the validity of such results, the authors used a coding scheme applied to the results by using a score of 1 or 2. In that regard, 2 denotes high appropriateness, while 1 denotes low appropriateness. The screening was carried out in two phases by three independent researchers with previous knowledge on the topic. The first phase evaluated the title and abstract, while the second one referred to the read of the whole paper. Then the authors computed inter-rater reliability for each paper by considering the difference in scoring. In the case the three independent scores came to the same conclusion (i.e., zero differences or the highest interrater reliability), the papers were considered. On the other hand, if differences in the scores occurred, related papers were discussed to result in a total agreement between the experts. This analysis finally resulted in 32 articles [29-60], that have been used as starting content for the development of the guidelines. Furthermore, the authors categorized each article basing on its content and main results and according to the four main categories that can characterize a CAS (see Table 1 for details) [28]: (i) workstation layout and elements, (ii) robot system features, (iii) robot system performance and (iv) organizational measures. Identified article topics and results are summarised in the following. In Table 1, each paper has also been categorized according to the cognitive variables explicitly addressed in the specific study.

Workstation Layout and Elements

Bitonneau et al. [40] presented a simulation-based approach for interactive and inclusive robot system design and observed an improvement in the design process effectiveness. El Makrini et al. [43] developed a collaborative architecture for enhanced HRI during assembly, allowing better human-robot communication, providing a personal experience, and allowing a more intuitive interaction. Gopinath et al. [46] presented a risk assessment-based design of a collaborative assembly cell by analyzing, among other things, how to manage human errors through feedback interfaces effectively.

Robot System Features

Tang et al. [30] analyzed the effect of light-based signaling systems for HRI and communication by improving user's awareness and reducing the workload. Changizi et al. [33] evaluated the use of the robot as an assistance system by using the hand-guiding modality, which users perceived as comfortable, controllable, and helpful. Richert et al. [39] examined the relationships between robot design and personality and discovered that humanoid appearance might be better in the case of close (industrial) collaboration. Kadir et al. [41] identified the emerging opportunities, challenges, and critical design factors in HRI that need to be addressed to maximize the technology's benefits. Fu and Zhang [42] modeled a robot design scheme from the perspectives of emotions and psychology and provided a set of indications to make people feel comfortable and safe. Müller et al. [47] examined the impact of the robot's appearance and behavior on team performance and human trust and found that an industrial appearance leads to better collaborative performance without influencing trust levels. In another work, Müller et al. [48] analyzed the subjective stress level in HRI and found that the robot's appearance and behavior do not affect the subjective stress level. Richert et al. [49, 53] preliminarily introduced and discussed the effects of appearance and behavior on human trust and stress level in HRI by using a virtual simulation. Johnson et al. [52] investigated the effectiveness of different light indicators for HRI and found that the light system integrated with the robot presented the shortest human reaction time. Schmidtler et al. [55] discussed the effect of robot arm contrast in HRI revealed that higher contrasts lead to higher operator distraction. Weistroffer et al. [56] provided a methodology to assess the acceptability of HRI and showed that a more anthropomorphic robot, both in its appearance and movements, is not necessarily better accepted by the users in a collaboration task.

Robot System Performance

Rojas et al. [29] proposed a more human-like trajectory-planning for collaborative robots, which users perceived as less stressful. Kaufeld and Nickel [31] provided evidence for lower mental workload when robots acted less autonomously while the operator was informed (by audio-visual signals) about upcoming HRI. Petruck et al. [34] presented an ergonomic concept for collaborative workstations to avoid high mental load by discussing the understandability and predictability of robot actions as well as its acceptance and trust. Koppenborg et al. [45] investigated the robot's motion speed and predictability in HRI, discovering a decrease in task performance for a lower level of predictability, while faster movements resulted in higher values for task load and anxiety. Müller et al. [48] analyzed the subjective stress level in hybrid collaborations and found that the robot's appearance and behavior do not affect the subjective stress level. Richert et al. [49, 53] preliminarily introduced and discussed the effects of appearance and behavior on human trust and stress level in HRI by using a virtual simulation. Weistroffer et al. [56] provided a methodology to assess the acceptability of HRI and showed that a more anthropomorphic robot, both in its appearance and movements, is not necessarily better accepted by the users in a collaboration task. Brecher et al. [57] developed methodologies and techniques to transform human movement trajectories so that industrial robots can execute them to improve operator's acceptance. Kuz et al. [58] and Mayer et al. [59] studied anthropomorphism in HRI and found that anthropomorphic characteristics embedded into the motion of industrial robots can have positive effects on the prediction time and accuracy of the human co-worker. Bortot et al. [60] discussed the effects of robot motion trajectory on humans and showed that variable (i.e., non-predictable) robot motions reduce human wellbeing and performance.

Organizational Measures

Bragança et al. [32] investigated the potential use of collaborative robots as assistance systems, also focusing on the cognitive aspects. Nelles et al. [35] reviewed the scientific literature to analyze the metrics for the evaluation of different variables associated with human wellbeing and system performance in HRI. Schleicher and Bullinger [36] empirically validated a mixed-method framework for the user-centered design of HRI by developing an assistive surface-finishing robot. Rosen et al. [37] developed and validated a toolkit enabling the evaluation of the

quality of HRI in different types of collaborative workplaces through multiple cognitive variables. Fletcher et al. [38] identified the requirements and gaps in ethics and safety standards for HRI, considering the effects of trust and acceptance. Charalambous et al. [44] presented a theoretical framework of key organizational human factors relevant to industrial HRC by developing a readiness level. Charalambous and Stout [50] discussed the application of HRC in a case study from a human factors perspective. In another study, Charalambous et al. [51] developed a roadmap with key human factors that need to be considered in the design of HRI and, in [54] they explored the key organizational human factors to be considered for the development of HRC.

Table 1. Articles classification according to main cognitive variables and related interaction variables.

Main Cognitive Variable	Interaction Variable			
	Workstation Layout and Elements	**Robot System Features**	**Robot Systems Performance**	**Organizational Measures**
Trust		[42] [47] [49]	[34] [49]	[35] [38]
Usability	[41] [46]	[30]		[35] [36] [37]
Frustration	[41]			
Perceived enjoyment				[37]
Acceptance	[43]	[33] [39] [56]	[34] [56] [57] [58] [59]	[35] [37] [38] [44] [50] [51] [54]
Stress	[41] [46]	[42] [48] [49] [53] [55]	[29] [34] [45] [48] [49] [53] [60]	[35] [37]
Cognitive workload	[40]	[30] [52]	[31] [34]	[32] [35] [37]

Even if different aspects of human factors in industrial HRI have been studied in the last years, a set of inclusive and human-centered design principles for the proper integration of cognitive ergonomics in CASs is missing. In particular, a guide for non-experts in cognitive ergonomics to be applied during the early design stage as well as for the setting of the interaction conditions could be particularly useful for industrial companies, especially for Small and Medium-sized Enterprises (SMEs).

c. Research questions

The present work aims to develop and evaluate a set of design guidelines for cognitive ergonomics in CASs. The main assumption to be tested is that it is possible to improve the

operator's experience and assembly performance by manipulating the system features and interaction patterns according to the design guidelines proposed in this work. According to this hypothesis, the following research questions are derived:

RQ1: What are the main design principles to be applied when designing or setting a CAS according to cognitive ergonomics?

RQ2: What is the operator's response when manipulating the features and parameters associated with these design principles?

RQ3: What are the effects on assembly performance?

2. Materials and Methods

a. Guidelines development and classification

The following guidelines were developed according to the content of the identified relevant papers founded by systematically analyzing the scientific literature. Therefore, the indications have been developed by properly combining and interpreting the conclusions of such validated works. In the case of possible contradictive suggestions in the analyzed studies, the authors discussed finding the best interpretation. The relationship between each guideline and related references is represented in the fourth column of Table 2. The authors believe that a "guideline" should be as general as possible, even if it should contain technical suggestions without being too detailed. This is necessary to leave designers the possibility to interpret the indications by guiding them towards a range of possible solutions. The guidelines are classified according to the four abovementioned interaction variables and summarized in Table 2.

Table 2. Guidelines for the design of CASs (workstation) considering cognitive ergonomics requirements.

Interaction Variable	Code	Guideline	Reference
Workstation Layout and Elements	WE.CE.1	Provide measures to transfer the graphic user interface onto the collaborative workspace;	[36]
	WE.CE.2	Locate the robot arm as distant as possible from the operator's position;	[35] [55] [56]
	WE.CE.3	Design low-contrast workstation elements with respect to the robotic system;	[55]
Robot System Features	RF.CE.1	Realize a fluent and smooth robotic system design (avoid bulky joints, wires, external arm components, mechanized shape);	[33] [50] [53]

	RF.CE.2	Design cold-white robot arm;	[33]
	RF.CE.3	Design a low-contrast robot arm with respect to the workstation elements;	[55]
	RF.CE.4	Design robotic system and related devices with industrial appearance (avoid adding human-like features, e.g. anthropomorphism, and social appearance for robotic systems to be used in industrial contexts);	[48] [50] [53] [56]
	RF.CE.5	Design on-board devices (mounted on the external surface of the robotic system) for the visual communication of the status of the robotic system;	[30] [52]
	RF.CE.6	Demonstrate the operators about the effectiveness and reliability of safety measures of the robotic system;	[30] [31] [50]
	RF.CE.7	Demonstrate the operators about the efficiency and operational reliability of the robotic system (e.g. the end-effector);	[30] [31] [50]
Robot Systems Performance	RP.CE.1	Design human-like-inspired/smooth/fluent and non-disruptive robotic system actions;	[29] [44] [46] [50] [56] [57] [58] [59]
	RP.CE.2	Provide measures for the implementation of a medium-level robotic system autonomy;	[31]
	RP.CE.3	Provide measures for the manual adjustment of robot arm speed according to operator's needs;	[33]
	RP.CE.4	Design comprehensible and predictable robotic system actions (avoid supposedly arbitrary actions of the system);	[34] [50] [56] [58] [59] [60]
	RP.CE.5	Provide measures for the automatic adaptation of robot arm speed to correspond with an operator's profile (i.e. expertise, skills, capabilities, preferences, trust level);	[38]
	RP.CE.6	Design slow robotic system actions and related motions (related to the kind of collaborative task);	[36] [50] [55] [56]
	RP.CE.7	Avoid unreliable/inaccurate performance of the robotic system;	[48] [49] [50]
	RP.CE.8	Inform the operator about the robotic system speed;	[60]
	RP.CE.9	Inform the operator about the robotic system behavior/state;	[60]
	RP.CE.10	Avoid variations in robot arm velocity;	[60]
Organizational Measures	OM.CE.1	Suggest work breaks to improve performance and concentration (suggestions could be based on age and the monitoring of psychophysical parameters);	[32]
	OM.CE.2	Provide information about the workstation systems (including the robotic system) only when relevant and necessary;	[32]
	OM.CE.3	Provide measures that allow the operators to control the workstation systems (including the robotic system);	[38]
	OM.CE.4	Inform operators about the type and functioning of the specific safety measures implemented in the workstation;	[38]

OM.CE.5	Provide functions of the workstation systems (including the robotic system) that adapt to suit individual operator's preferred working methods;	[38]
OM.CE.6	Provide workstation systems (including the robotic system) that adapt safety strategy to suit operator's preferences and conditions in the surrounding area;	[38]
OM.CE.7	Engage operators in workstation and interaction design (layout, assembly cycle, robotic system performance and motions);	[30] [31] [35] [49] [51] [54]
OM.CE.8	Demonstrate the operator about the efficiency and reliability of the robotic system role;	[30] [31] [39] [50] [53]
OM.CE.9	Inform the operator about upcoming HRI;	[31]
OM.CE.10	Provide as much as possible natural and intuitive communication between the operator and the robotic system;	[44]
OM.CE.11	Provide training and empowerment to the operator (understand the abilities, the process complexity, the limitations of the robotic teammate and the reasons behind the events);	[45] [49] [50] [51] [53] [54]
OM.CE.12	Visualize alternative decisions to reduce biases in decision-making;	[32]
OM.CE.13	Minimize the number of feedback interfaces;	[47]
OM.CE.14	Inform the operator about the collaboration mode change (e.g. from automatic to collaborative);	[47]

Legend
WE=Workstation Layout and Elements; RF=Robot System Features; RP=Robot System Performance; OM=Organizational Measures; CE=Cognitive Ergonomics;

b. Cognitive ergonomic evaluation metrics

In the following section, the primary cognitive variables and related risk factors to be tested are described according to the scientific literature. These will be used to quantify and assess the effectiveness of the developed guidelines through an experimental case study.

- *Trust*: can be defined as the willingness to take the risk of being vulnerable to the actions of others regardless of the ability to control those actions [61]. Trust develops dynamically with knowledge and experience and is often addressed as a calibration process between the actual reliability of the system and the level of trust posed by the person interacting with it. Risk arises following a dysfunctional calibration, which can lead to over-trust or distrusts [62].
- *Usability*: refers to the extent to which a system, product, or service can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use [63, 65]. Usability has been mentioned to be at the foundation of success before the market introduction or application of a specific technology [64]. It is linked with the

acceptance of technology, and authors argued that the introduction of a new system might be useless unless it is liked and thus used by target users. Lack of usability can imply multiple risk factors for workers such as incorrect task execution, high ratio of failure resulted from human errors, longer execution time of a task, bad responses from users, loss of information, making the work environment more prone to hazards [64].

- *Frustration*: is a psychological state derived from an unsatisfied need or unresolved problems. It is linked to increased speed of performance and increased error rate, particularly in complex tasks [65];
- *Perceived enjoyment*: it is a feeling of joy or pleasure associated by the user with the use of the system. It has been studied in relation to robots' acceptance and intention to use. Lack of perceived enjoyment can lead to lower levels of acceptance of the system and thus a lower intention to use [66].
- *Acceptance*: technology acceptance is the favorable reception of technology as a useful and practical tool [67, 68]. A low level of technology acceptance may introduce a risk for workers as it could compromise the success of interaction between humans and robots;
- *Stress*: in general, it is defined as the human body's response to pressures from a situation or life event [69]. When this pressure exceeds certain limits, stress becomes a risk factor, as it can have a detrimental effect on performance and can lead to an increased error rate;
- *Cognitive workload*: refers to the cognitive effort that an individual shows during a task or to achieve a particular level of performance [70]. Assuming that an individual's cognitive resources are limited, the more effort is requested by a task, and the higher is the cognitive workload. It affects both safety and performance;

c. Experimental set-up

The effectiveness of the guidelines has been evaluated through multiple experiments based on a HRI case study performed in the Smart Mini Factory (SMF) laboratory [72]. This is a laboratory for teaching and research in the field of the main technologies of Industry 4.0, particularly focusing on sustainable manufacturing systems and robotics. The experiment was conducted by using a dedicated workstation (a CAS) for the collaborative assembly of a manufacturing product. This was a simplified version of a pneumatic cylinder from Kuhnke (see Figure 1) (diameter of 32 mm and 50 mm stroke) with roughly 20 different parts. To decrease the

complexity of the tasks and to reduce the assembly time, the structure of this product has been simplified to 14 parts. A description of the overall assembly process can be found in [7171].

Figure 1. Pneumatic cylinder from Kuhnke.

The main components of the workstation are following described (see Figure 2).

- (1) Collaborative robot model Universal Robots UR3 [73] equipped with a (2) Robotiq [74] collaborative gripper;
- (3) Fixed working table with assembly jigs;
- (4) Commands (button array) for HRI and emergency stop;
- (5) Virtual button (to be activated using the AI-based 3D perception device and vision system);
- (6) Boxes for the storing and picking of assembly parts;
- (7) LCD screen for displaying instructions and other information about the status of the robotic systems (graphic user interface (GUI));
- (8) AI-based 3D perception device and vision system (Smart Robots [80]) for HRI (it allows the implementation of the gesture recognition) and safety purposes (it allows the implementation of a collision avoidance safety measure);
- (9) Screwdriver (Fiam) [81].

Furthermore, the workstation was designed to provide three main workspaces:

- The human workspace. It was defined at the right and left sides of the collaborative workspace (the robotic system cannot reach this area). This space was intended for the participant for reaching the storage boxes, using the button array and the virtual button, interact with the GUI;
- The collaborative workspace. It was defined between the participant and the robotic system in front of the participant's seat (both the participant and the robotic system can reach this area). This common space was intended for the manual assembly of the product as well as for physical HRI;

- The robotic system workspace. It was defined as the opposite of the collaborative workspace (the participant cannot reach this area while sitting). This space was intended for the robotic system to pick up and handle the parts to be manipulated autonomously.

According to the different sets of guidelines to be tested, the listed features and related interaction modalities have been changed. The components were mounted on the top of the working table. The collaborative robot was placed in the center of the working table so that its end-effector was able to reach both the collaborative and the robot workspace easily. A set of jigs was fixed in front of the participant in the collaborative workspace. There was the option to integrate foam protections around the jigs to enhance safety and visibility. It was possible to add highlighting components to the robotic system to increase the visibility of moving parts. The boxes for the storage of the assembly parts were placed on the left side of the human workspace. The buttons array and the LCD screen were also located in the same area to facilitate the participant's activities, while the virtual button was located on the right side of the human workspace. The AI-based 3D vision system was installed on an aluminum structure in front of the human workspace to frame the operator's motion and her/his reachable space. The working table boundaries were covered with colored adhesive tapes to increase the visibility of the corners. The screwdriver was located on the right side of the human workspace in line with the operator's head.

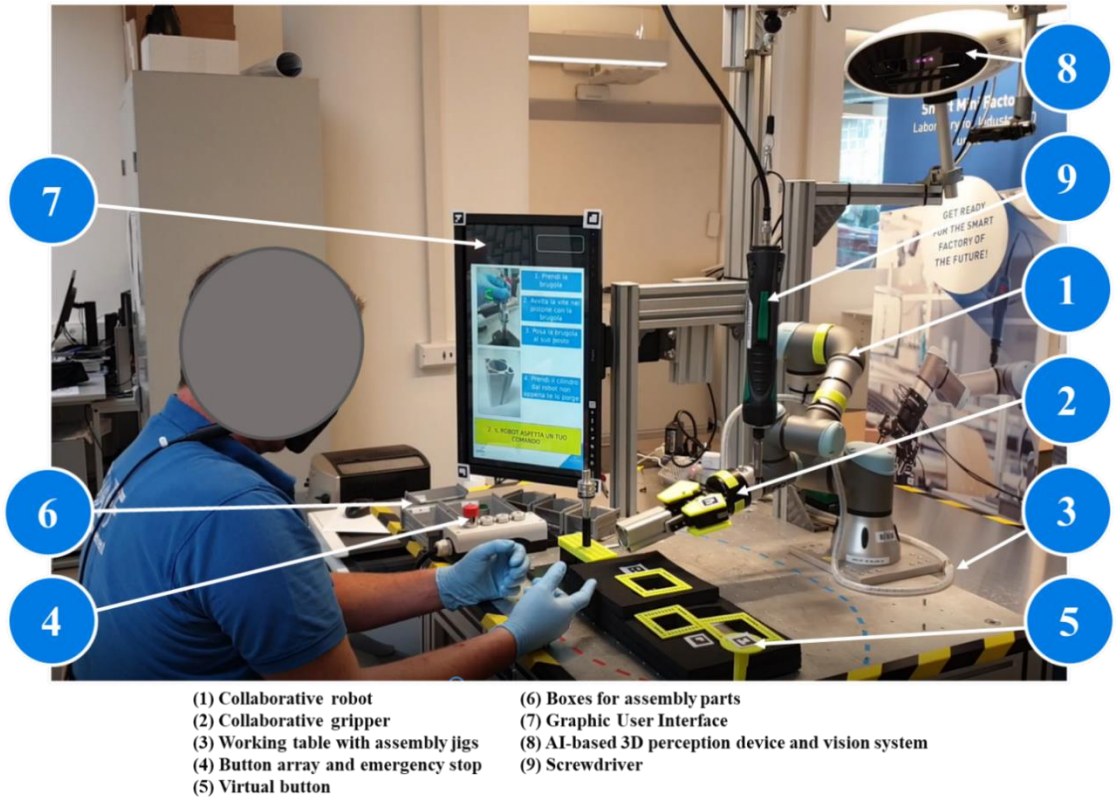

Figure 2. Experimental set-up.

Beyond the equipment's physical arrangement, another design aspect that is worth to be described is the architectural design. Architectural design is the representation of the communication infrastructure that links all the entities of a system. In this application, there were five main actors taking part in the data exchange: the robot's controller, the robot's arm (and the integrated collaborative gripper), the microcontroller (that manages the output to the LCD screen) and, the buttons array. The controller of the robot was the core component of the system. The robot's arm and the buttons array were physically wired to the robot's controller. The AI-based 3D vision system and the microcontroller for managing the LCD screen communicated with the robot's controller through the XML-RPC (eXtensible Markup Language – Remote Procedure Call) protocol. The software running on the microcontroller (a Raspberry Pi 4) was a Python script that absolved two main tasks: (i) receiving commands from the robot's controller and (ii) transforming them into meaningful information for the operator. The Python script was able to generate on-screen popup notifications and manage the instructions shown on the GUI (provided in OpenOffice

slideshow format). The chosen AI-based 3D vision system is a plug-and-play device and did not require any peculiar adjustment for the interaction with the robot's controller.

d. Experiment description and scenarios

Advertisements about the possibility to participate in the experiment were sent through emails channels and social networks of the Free University of Bozen-Bolzano. The requisite for inclusion was not having previous experience in HRI and at least minimal experience in manufacturing operations or DIY. The experimenters verified the requisites through a brief unstructured interview during the first contact with candidates.

A total of 14 participants were involved in the study: 12 males and two females. The age of participants ranged from 23 to 57 years old. Due to constraints related to the COVID-19 pandemic, it was possible to enroll only people who had some involvement with the University of Bozen-Bolzano (primarily for the safety of participants and insurance-related reasons), thus regarding participant occupation, six of them were researchers, one master student, and seven technicians/administrative.

The participants were asked to collaborate with the low-payload collaborative robotic system to complete the assembly of the simplified pneumatic cylinder. Firstly, a training session (without the robotic system) was provided in a dedicated training workstation to reduce the occurrence of possible errors related to limited and heterogeneous knowledge of the product and process. We sought this as a way to reduce the influence of the learning effect on the results. Additionally, instructions about the necessary steps to complete the task were displayed on the workstation LCD screen across the experiments. Later, the participants moved to the collaborative workstation and performed the assembly tasks in collaboration with the robotic system. Table 3 explains how the guidelines were implemented and manipulated in the experimental case study. Unfortunately, it was not possible to test all the guidelines in the present experiment because implementing all the related solutions at the same time was not feasible from a technical standpoint. In other cases, the achievable results would have resulted redundant with other applied guidelines (potentially providing a detrimental effect to the experiment). Furthermore, some guidelines referred to generic industrial HRI and were not specifically applicable to HRC, as proposed in this case study (see i.e. WE.CE.2). Further details about the guidelines that were not implemented in the experiment will be provided in the discussion section (see also Table 8).

Table 3. Guidelines implementation (solutions) in the experimental case study.

Code	Guideline	Solution for the implementation
WE.CE.1	Provide measures to transfer the graphic user interface onto the collaborative workspace;	Multiple highlighting-yellow components have been designed and realized through 3D printing techniques. The aim was to highlight the CAS components, which are crucial for the assembly as well as for the HRI (booth for fixes and moving parts of the workstation).
RF.CE.1	Realize a fluent and smooth robotic system design (avoid bulky joints, wires, external arm components, mechanized shape);	This characteristic was intrinsically present in the design of the robotic system and related devices used in the experiment.
RF.CE.4	Design robotic system and related devices with industrial appearance (avoid adding human-like features, e.g. anthropomorphism, and social appearance for robotic systems to be used in industrial contexts);	The workstation has been realized with industrial components. The environment in which the experiment has been conducted was similar to a manufacturing environment.
RF.CE.6	Demonstrate the operators about the effectiveness and reliability of safety measures of the robotic system;	An introductory safety training has been developed. It aimed to explain to the participants the main safety measures of the robotic system through a live demonstration.
RP.CE.1	Design human-like-inspired/smooth/fluent and non-disruptive robotic system actions;	A minimum-jerk trajectory [29] has been integrated into the motion of the robotic system. This trajectory is mainly used for its similarity to human-joint movements and for the possibility to limit robot vibrations.
RP.CE.2	Provide measures for the implementation of a medium-level robotic system autonomy;	This has been implemented through: - different levels of autonomy in the robot tasks (reached by changing the programming of the robotic system by considering a level 3 on the LORA scale [82]); - different control commands that the operator can give to the robotic system.
RP.CE.3	Provide measures for the manual adjustment of robot arm speed according to operator's needs;	This has been implemented by using a button array. By pressing one of the available buttons, the speed changed accordingly. It was possible to choose: low speed (75% of the programmed nominal value*), nominal speed (100% of the programmed nominal value*) and, high speed (125% of the programmed nominal value*);
RP.CE.6	Design slow robotic system actions and related motions (related to the kind of collaborative task);	This has been implemented by changing the robot speed (through programming) for each scenario. The program can be set to: high speed (scenario 1 - 125% of the programmed nominal value*); low speed (scenario 2 - 75% of the nominal value*) and, nominal speed (scenario 3 - nominal value*).
RP.CE.7	Avoid unreliable/inaccurate performance of the robotic system;	The assembly cycle has been previously tested to avoid possible errors related to the robotic tasks. The robotic system and related devices were state of the art and reliable.
RP.CE.8	Inform the operator about the robotic system speed;	This has been implemented by using the GUI developed by the research team, which also included the possibility of displaying popup notifications containing information about the status of the

		robotic system. In particular, the information graphically explained the selected speed of the tool center point of the robotic system (see RP.CE.3): slow, nominal, high.
RP.CE.9	Inform the operator about the robotic system behavior/state;	This has been implemented by using the GUI, which also included the possibility of displaying popup notifications containing information about the status of the robotic system: on operation, on position, stopped due to a command, stopped due to collision avoidance. In particular, the information explained the robotic system's status according to the command given by the operator (see OM.CE.3) and according to the interaction conditions.
RP.CE.10	Avoid variations in robot arm velocity;	This has been implemented by programming the robot's motion in such a way as to keep a relatively constant speed and acceleration of the arm. In case of min. jerk trajectories, this kind of condition was more complicated to be satisfied.
OM.CE.2	Provide information about the workstation systems (including the robotic system) only when relevant and necessary;	This has been implemented by using the GUI, which also included the possibility of displaying popup notifications containing information about the status of the robotic system. The GUI was designed to avoid overloading the operator with useless or not meaningful information.
OM.CE.3	Provide measures that allow the operators to control the workstation systems (including the robotic system);	This has been implemented by: - allowing the participants to arrest and resume the motion of the robotic system by using the gesture recognition functionalities provided by the AI-based 3D perception device and vision system; - allowing the participants to control the robot speed (see RP.CE.3).
OM.CE.4	Inform operators about the type and functioning of the specific safety measures implemented in the workstation;	This has been implemented by training the participants about the safety measures that operated during the upcoming scenario. In addition, a notification about possible collision avoidance was provided by the GUI.
OM.CE.8	Demonstrate the operator about the efficiency and reliability of the robotic system role;	This has been implemented by training the participants about the roles and responsibilities of the robotic system and related devices.
OM.CE.10	Provide as much as possible natural and intuitive communication between the operator and the robotic system;	This has been implemented by properly deign the interfaces that allowed the HRI and communication (buttons, GUI, gesture recognition based on the AI-based 3D perception device and vision system).
OM.CE.11	Provide training and empowerment to the operator (understand the abilities, the process complexity, the limitations of the robotic teammate and the reasons behind the events);	This has been implemented by training the participants about the assembly cycle (process) and related products.
OM.CE.13	Minimize the number of feedback interfaces;	This has been implemented by using the GUI, which was designed to avoid overloading the operator with useless or not meaningful information.

* the nominal value of the robot speed was set according to a preliminary mechanical risk assessment by following the ISO TS 15066 [83] requirements. This evaluation has resulted in conservatively estimated speed values of the robot.

The experiment consisted of executing the assembly task in three different and sequential scenarios (Scenario1, Scenario 2 and, Scenario 3, respectively). According to the different scenarios, different guidelines were applied, and therefore the features of the workstation changed accordingly. The assignment of the scenarios was non-randomized. The idea was to provide them in such a way as to improve the interaction conditions by gradually changing the solutions implemented by the different guidelines. We assumed that Scenario 1 would be the worst one, while Scenario 2 and 3 were supposed to be gradually better from a cognitive perspective. A summary of the application of the guidelines according to different scenarios is presented in Table 4. The presumed worst case (Scenario 1) was supposed to simulate a CAS developed without accounting for human factors during the design process. Considering state of the art, Scenario 1 can reasonably represent most of the current real industrial applications. Scenario 2 would have to represent an intermediate case. Finally, we expected that Scenario 3 simulated the best interaction conditions.

Table 4. Application of the guidelines according to different scenarios.

Applied guideline (code)	Scenario 1	Scenario 2	Scenario 3	Operator's dependency *
	The expected worst-case from the cognitive point of view	**The expected intermediate case from the cognitive point of view**	**The expected best case from the cognitive point of view**	
WE.CE.1	NO (No CAS components were highlighted)	YES (CAS components which are crucial for the assembly as well as for the HRI were highlighted)	YES (CAS components which are crucial for the assembly as well as for the HRI were highlighted)	NO
RF.CE.1	YES (intrinsic design of the robotic system and related devices)	YES (intrinsic design of the robotic system and related devices)	YES (intrinsic design of the robotic system and related devices)	NO
RF.CE.4	YES	YES	YES	NO
RF.CE.6	NO	YES	YES	NO
RP.CE.1	NO	NO	YES	NO
RP.CE.2	NO (the robot autonomy was the lowest; there was no possibility to command the robotic system)	YES (partially: the robot autonomy was the highest; there was the possibility to control the robotic system)	YES (totally: the robot autonomy was intermediate; there was the possibility to control the robotic system)	YES
RP.CE.3	NO	NO	YES	YES
RP.CE.6	NO (fast situation: robot speed equal to 125% of the nominal value)	YES (slow situation: robot speed equal to 75% of the nominal value)	YES (robot speed equal to the nominal value, which means a	NO

			safe speed according to the application)	
RP.CE.7	YES	YES	YES	NO
RP.CE.8	NO	NO	YES	NO
RP.CE.9	NO	YES	YES	NO
RP.CE.10	YES	YES	YES (min. jerk)	NO
OM.CE.2	YES	YES	YES	NO
OM.CE.3	NO	YES (partially: participants could control the motion of the robotic system)	YES (totally: participants could control the motion of the robotic system)	YES
OM.CE.4	NO	YES (partially: provided by training)	YES (totally: provided by training and by GUI notifications)	NO
OM.CE.8	YES	YES	YES	NO
OM.CE.10	YES (partially: the robotic system's command was given by a physical touch on the end-effector)	YES (partially: the robotic system's command was given by using a virtual button)	YES (totally: the participants could choose the way of interaction they prefer (touch or virtual button))	YES
OM.CE.11	YES	YES	YES	NO
OM.CE.13	YES (the GUI provided only the instructions)	YES (the GUI provided the instructions and the notifications about the robotic system status)	YES (the GUI provided the instructions and the notifications about the robotic system status and speed)	NO

* A value equal to "YES" means that the operator has the chance to decide whether or not to activate the technical solution implemented by following the associated guideline. In other words, such solutions are operator's dependent.

e. *Measures*

A survey was administered to participants to assess how manipulating features in each scenario would affect their overall experience and opinions about the collaboration in different experiment phases. Participants were asked to complete the survey before starting the experiment and in between each scenario. In particular, the same questions were repeated after the conclusion of each scenario. The survey was designed to provide results according to the cognitive risk factors previously identified. The feedback allowed the authors to gain knowledge directly from the participants' experiences and perceptions under different experimental conditions. The survey assessed included the following sections.

Acceptance. Users' acceptance towards the robot was assessed using the System Acceptance Scale [75]. It includes nine semantic differential items representing different attitudes

toward the technology. Participants were asked to rate on a five-point scale (from -2 to +2) what level of these adjective continuums (e.g., “Effective/Superfluous”, “Pleasant/Unpleasant”) they attributed to the robotic system. The items were grouped into two sub-scales, one indicating the system’s perceived usefulness and the other the satisfaction resulting from the use of the technology. Cronbach’s alpha reliability coefficient was 0.89.

Cognitive Workload. Participants were asked to rate on a 5-point Likert-type scale (1 = very low; 5 = very high) a single item (i.e., “How mentally demanding was the task?”) taken from the NASA-Task Load Index (NASA-TLX) [76].

Frustration. Participants’ perceived frustration in collaborating with the robotic system was assessed through a single item (i.e., “Did you experience frustration while performing the collaborative task with the robot?”) rated on a 5 point scale (1 = not at all; 5 = a lot).

Perceived Enjoyment. Participants’ perceived enjoyment related to interacting with the robotic system was as well assess through a single item (i.e., “Did you enjoy interacting with the robot?”) rated on a 5 point scale (1 = not at all; 5 = a lot).

Perceived stress. Stress was assessed using the Short Stress State Questionnaire (SSSQ) [78]. Participants were asked to think about how they felt during the execution of the task and rate 5 semantic-differential items (e.g., “At ease/Discomfort”, “Irritated/Calm) on a 5 point scale. A Cronbach’s alpha reliability coefficient of 0.67 indicated poor reliability of the scale in the current sample.

Trust. Participants’ trust towards the collaborative robot was assessed using a slightly re-adapted version of the Trust in Industrial Human-Robot Collaboration Scale [77]. The scale consisted of nine items (e.g., “The speed at which the gripper picked up and released the components made me uneasy”; “I trusted that the robot was safe to cooperate with”; “The gripper seemed like it could be trusted”) rated on a five-point Likert scale. Cronbach’s alpha reliability coefficient was 0.73.

Usability. Perceived usability has been measured using five items taken from the System Usability Scale [79]. Items were slightly re-adapted to address robotic systems. All items were rated on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). Participants were asked to express their level of agreement with the following statements: (1) “I think I would like to use the robot frequently”; (2) “I found the robot’s behavior to be mostly predictable”; (3) “I found the various functions in the robot were well-integrated”; (4) “I found the robot to work

appropriately."; (5) "I found that the robot could be operated and managed intuitively". Cronbach's alpha reliability coefficient was 0.76.

To further integrate the data obtained from the survey, different collection methods for qualitative data have been used. These are following described.

- Direct observation during the execution of the experiment: the behavior of the participants was directly observed by the testers during the experiments. The aim was to collect as much feedback as possible by noting particular events or situations (errors, near misses, and participant's requests);
- Video recording: all the experiments were recorded by using a camera system. The recordings were used after the conclusion of the experiments to perform further detailed observations;
- Semi-structured interview: some oral and informal discussions between the participant and the testers were conducted at the end of each experiment. The aim was to collect further information not expressed by the participants during the questionnaire's fulfillment (e.g., particular observations made by participants that they want to share).

3. Results

Table 5 and Figure 3 summarize the main outputs obtained from the survey. It is relevant to mention that each scenario's duration was mainly dependent on the participants' ability to deal with the specific assembly situation (i.e., ability to use the available tools, number of assembly errors, reasoning time according to various events, etc.). On average, the duration of each scenario was the following:

- Scenario 1 lasted 228.3 s for each participant (with a standard deviation of 17.5 s);
- Scenario 2 lasted 221.2 s for each participant (with a standard deviation of 15.7 s);
- Scenario 3 lasted 213.0 s for each participant (with a standard deviation of 18.6 s).

Table 5. Mean and Standard Deviation (SD) of cognitive risk factors according to different scenarios.

Risk Factor	Scenario 1		Scenario 2		Scenario 3		Mean values difference between Scenario 1 and Scenario 2 (%)	Mean values difference between Scenario 2 and Scenario 3 (%)
	Mean	SD	Mean	SD	Mean	SD		

Trust	4.29	0.76	4.56	0.72	4.79	0.35	+6%	+5%
Usability	4.09	0.83	4.36	0.77	4.33	0.75	+6%	-1%
Frustration	1.64	1.15	1.36	0.84	1.21	0.58	-17%	-11%
Perceived Enjoyment	3.93	1.27	4.36	0.84	4.36	0.84	+10%	0%
Acceptance	3.80	0.98	4.18	0.55	4.18	0.70	+9%	0%
Stress	1.80	0.71	1.40	0.71	1.31	0.35	-22%	-7%
Cognitive Workload	0.93	1.14	1.07	1.21	0.57	1.09	+13%	-47%

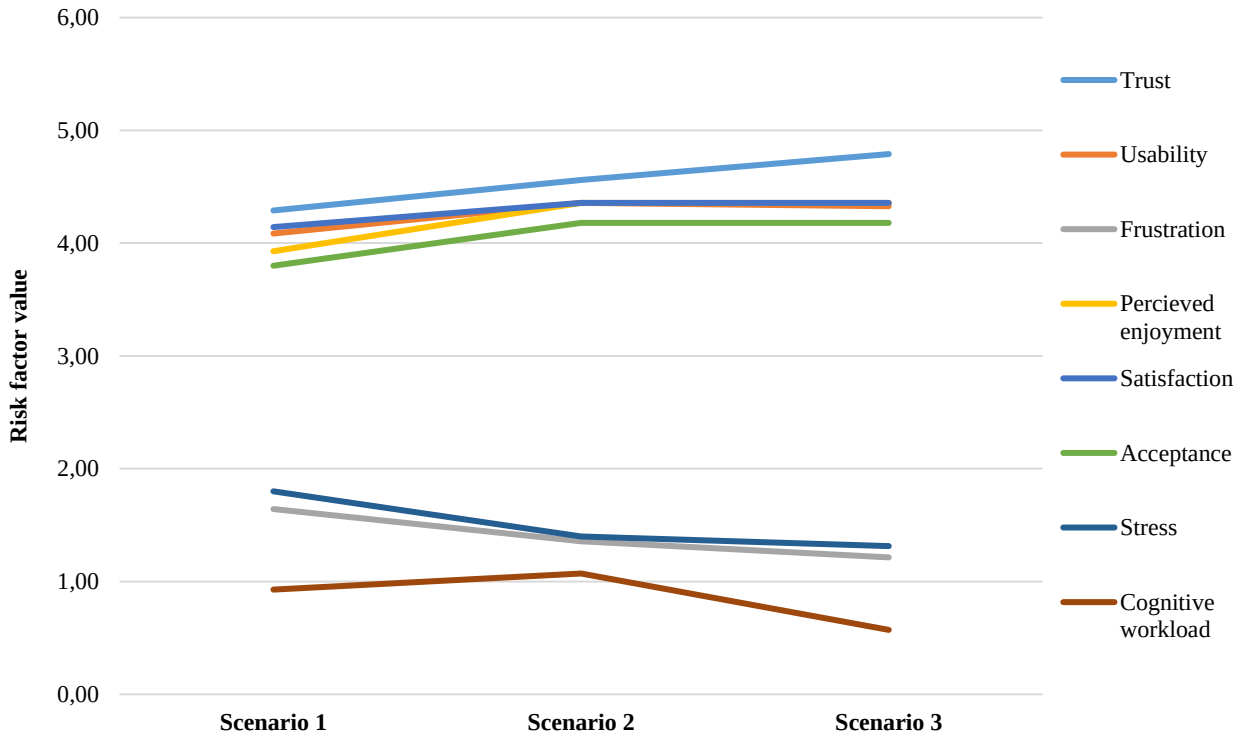

Figure 3. The trend of cognitive risk factors according to different scenarios.

To assess differences in duration and participants' cognitive risk factors scores in each scenario, a multiple repeated measure ANOVA analysis using SPSS v23 was performed.

Scenario duration was significantly affected by the changes in workstation features $F(2,26) = 14.62$, $p < .001$. Bonferroni post-hoc tests indicated that the mean scores of duration in Scenario 2 and Scenario 3 were significantly lower than in Scenario 1 ($p < .005$; $p < .005$).

Acceptance was significantly affected by each scenario's different features, $F(2,26) = 8.20$, $p < .005$. Bonferroni post-hoc tests indicated that the mean scores on acceptance in Scenario 3 were significantly higher than in Scenario 1 ($p = .05$; $p = .005$).

The perceived cognitive workload was significantly affected by each scenario's different features, $F(2,26) = 5.02$, $p = .01$. Bonferroni post-hoc tests indicated that the mean score on perceived cognitive workload in Scenario 3 was significantly lower than in Scenario 2 ($p = .01$).

Perceived enjoyment was significantly affected by each scenario's different features $F(2,26) = 5.20$, $p = .01$. Bonferroni post-hoc tests showed a tendency to significance for mean score of perceived enjoyment. Perceived enjoyment in Scenario 2 and 3 was higher than in Scenario 1 ($p = .08$).

Participants' reported stress level was significantly affected by each scenario's different features $F(2,26) = 13.94$, $p < .001$. Bonferroni post-hoc tests indicated that the mean stress score in Scenario 2 and Scenario 3 was significantly lower than in Scenario 1 and ($p < .05$; $p < .01$).

Trust was significantly affected by each Scenario's different features $F(2,26) = 3.43$, $p < .05$. Bonferroni post-hoc tests showed no significant difference between estimated marginal means in each scenario.

The perceived usability was also significantly affected by each scenario's different features, $F(2,26) = 4.24$, $p = .03$. Bonferroni post-hoc tests indicated that the mean usability score in Scenario 3 was significantly higher than in Scenario 1 ($p < .05$).

Analysis of reported frustration scores showed no significant results. Table 6 displays the estimated marginal means of each considered variable in the three scenarios.

Table 6. Estimated marginal means of the dependent variables in each scenario.

D.V	Scenario 1	Scenario 2	Scenario 3
Scenario duration	246.93	221.21	213
Acceptance	3.80	4.18	4.18
Cognitive Workload	0.93	1.07	0.57
Perceived enjoyment	3.92	4.36	4.36
Stress	1.80	1.40	1.31
Trust	4.29	4.56	4.67
Usability	4.09	4.36	4.33

Frustration	1.64	1.36	1.21

Table 7 and Figure 4 summarises the main results provided by the video analysis (qualitative results). These were obtained by carefully watching the records to find possible critical events (for all the participants) during the experiment (for all the scenarios). The identified events were then discussed by a team of experts and classified as follow:

- Errors related to the assembly cycle (i.e., wrong sequence of tasks);
- Near misses related to abnormal behaviors concerning the assembly cycle (i.e., anticipating the grip of a component passed by the robotic system before the competition of its task);
- Requests made from the participants to the tester to understand/clarify certain situations (i.e., request clarification on the robotic system's status).

Table 7. Critical events for each scenario.

Scenario	TOT Errors	TOT Near Miss	TOT Requests	TOT Overall
Scenario 1	48	40	21	109
Scenario 2	23	19	8	50
Scenario 3	18	19	4	41

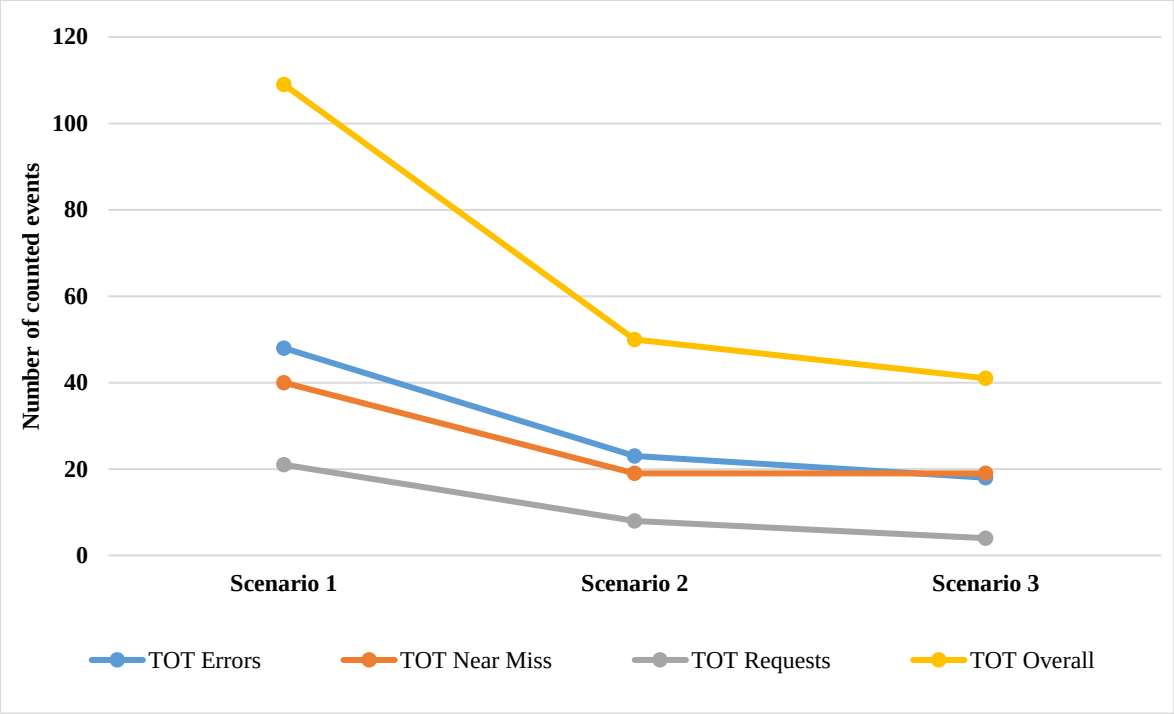

Figure 4. The trend of critical events according to different scenarios.

4. Discussion

In general, results provide preliminary support for implementing the identified guidelines and are in accordance with previous literature. In particular, according to the survey and interviews, results showed that:

1. Participants' acceptance, perceived enjoyment, and usability significantly improved as the identified guidelines were implemented in the subsequent scenarios. Analysis of contrasts showed that a significant improvement could be obtained even with a partial implementation of the guidelines in Scenario 2, while it was not possible to show a consistent improvement moving from Scenario 2 to Scenario 3. These results are essentially in line with previous literature [e.g., 37, 41, 43, 46, 54] and indicate which are the cognitive risk factors that can see the most benefits from the implementation of the identified guidelines.
2. Perceived Cognitive workload increased slightly by shifting from Scenario 1 to Scenario 2 (+13%) but considerably decreased from Scenario 2 to Scenario 3 (-47%). Analysis of contrast showed that the decrease in levels of reported cognitive workload in Scenario 3 was significant, while the slight increase in Scenario 2 compared to Scenario 1 was not significant. Again, this result is in line with previous research [30, 31, 37, 40, 52] and highlights that a more extensive

implementation of the proposed guidelines is needed to show reductions in participants' cognitive workload.

3. Reported stress levels decreased shifting from Scenario 1 to Scenario 2, and from Scenario 1 to Scenario 3. This result suggests that implementing guidelines can lead to a reduction in reported stress arising in the interaction with the robotic system and in doing the task, contributing to increasing knowledge on the matter. Similar studies do, in fact, show inconsistent results [48, 49, 53].
4. Frustration levels appeared to lower with the enhancement of workstation features and interaction conditions by shifting from the various scenarios (-17% in the first transition and -11% in the second one). However, it was not possible to highlight a statistically significant relationship. Also, trust appears to improve and be significantly affected by each scenario's features, but the analysis of contrasts did not show significant differences.

According to the video analysis, results showed that the overall number of critical events decreased with a complete implementation of the guidelines. In particular, they reduced respectively by a value equal to 25, 21, and 13 in the first transition and by a value equal to 5, 0, and 4 in the second one.

Results show support to the assumption that it is possible to improve participants' experience of HRI with the enhancement of workstation features and interaction conditions, suggesting that the proposed guidelines can improve cognitive variables and reduce the related risk factors for operators collaborating with robotic systems. Furthermore, according to the trend of the critical events, the assembly performance improved with a complete implementation of the guidelines. As expected, the best condition was related to Scenario 3, which was the scenario with the highest number of implemented guidelines. Nevertheless, according to the quantitative and qualitative data, the largest improvement came from the change between Scenario 1 and Scenario 2.

Similarly to other human factors and ergonomics frameworks related to HRC, such as the one developed by Kadir [84], the guidelines presented and evaluated in the current study could benefit from the integration with other human factors frameworks and techniques such as Cognitive Work Analysis (CWT) [85], Cognitive Tasks Analysis (CTA) [86], and Hierarchical Task Analysis (HTA) [87]. As it was suggested by Kadir [84], the developed guidelines could be further improved and refined through consultations and involvement with experts in CTA, CWT

and HTA. Similarly, those methods could draw important suggestions in their applications by the guidelines here presented.

According to the present results, we could argue that implementing human-like trajectories and allowing the operator to set the pace of the robotic system as well as choosing the preferred mode of HRI (i.e., physical pressure vs. a virtual button) contributed to improve participants experience and reducing related risk factors significantly. This is in line with previous literature [29], which showed that the introduction of human-like trajectories in robot movement patterns could increase the sense of predictability and familiarity in participants, reducing levels of perceived stress. Further support can be found looking at results on perceived usability and cognitive workload in Scenario 3. Higher predictability and a sense of familiarity mean that humans would use less cognitive resources to interact with the robotic system, thus lowering cognitive workload levels and leading to a lower rate of errors and near misses. Furthermore, the freedom of choosing the speed of the robot and the interaction channel were possibly instrumental features in reducing levels of stress and cognitive workload and increasing acceptance, perceived enjoyment, and usability. This could find a possible explanation in the self-determination theory [88] which states that intrinsic motivation thrives on autonomy, which comprises performing a task based on one's own volition. Results suggest that allowing the operator to adjust the system's features (e.g., robot speed) and choosing interaction channels (e.g., type of command) could lead to increased perceived usability through increased motivation. The self-determination theory in HRI has been recently used in the educational context [89], and our study suggests that it could have favorable implications in the industrial context as well.

As mentioned in the description of the experiment and related scenarios, it was not possible to test all the guidelines in the present experiment. Table 8 summarizes the guidelines that have not been implemented, also discussing the main reasons behind these choices.

Table 8. Guidelines that have not been implemented in the experiment.

Code	Guideline	Reason
WE.CE.2	Locate the robot arm as distant as possible from the operator's position;	According to the (collaborative) assembly cycle, the operator and the robotic system have to work nearby. Therefore, the position of the robot arm cannot be chosen arbitrarily due to functional requirements.

WE.CE.3	Design low-contrast workstation elements with respect to the robotic system;	It was not possible to continuously and quickly modify the color of the workstation elements according to the single scenario.
RF.CE.2	Design cold-white robot arm;	It was not possible to continuously and quickly modify the color of the robot arm according to the single scenario.
RF.CE.3	Design a low-contrast robot arm with respect to the workstation elements;	As for RF.CE.2.
RF.CE.5	Design on-board devices (mounted on the external surface of the robotic system) for the visual communication of the status of the robotic system;	To avoid information redundancy and according to OM.CE.13 (minimize the number of feedback interfaces), this guideline was not implemented. The visual status of the robotic system was communicated by using the GUI.
RF.CE.7	Demonstrate the operators about the efficiency and reliability of the robotic system (e.g. the end-effector);	To avoid influencing participants' cognitive responses, this demonstration was not done. Instead, it was done concerning the safety measures of the robotic system (RF.CE.6) in the second scenario.
RP.CE.4	Design comprehensible and predictable robotic system actions (avoid supposedly arbitrary actions of the system);	This guideline has been partially fulfilled by implementing RP.CE.1, RP.CE.6 and RP.CE.9, especially from the perspective of the robot motion.
RP.CE.5	Provide measures for the automatic adaptation of robot arm speed to correspond with an operator's profile (i.e. expertise, skills, capabilities, preferences, trust level);	The application of such a guideline will be very interesting. Nevertheless, its implementation will be too complex and time-consuming for a laboratory case study. In addition, due to the design of the experiment and the profile of the involved participants, some of the features (e.g. expertise, skills, capabilities) can be considered the same for all of them (at least by considering the group of researchers/students and the group of technicians/administrative).
OM.CE.1	Suggest work breaks to improve performance and concentration (suggestions could be based on age and the monitoring of psychophysical parameters);	Since the experiment is based on three sequential scenarios (each of which lasts about 5 minutes), the application of such a guideline was not necessary.
OM.CE.5	Provide functions of the workstation systems (including the robotic system) that adapt to suit individual operator's preferred working methods;	As for RP.CE.5.
OM.CE.6	Provide workstation systems (including the robotic system) that adapt safety strategy to suit operator's preferences and conditions in the surrounding area;	As for RP.CE.5.
OM.CE.7	Engage operators in workstation and interaction design (layout, assembly cycle, robotic system performance and motions);	Due to the structure of the experiment, participants did not have to know any details of the system/cycle before their experience. Therefore, this guideline was not implemented.
OM.CE.9	Inform the operator about upcoming HRI;	The experiment referred to HRC. The operator and the robotic system were supposed to collaborate continuously during the experiment. As a consequence, there are no other forms of HRI in the case study.

OM.CE.12	Visualize alternative decisions to reduce biases in decision-making;	To avoid making the participant's experience to complex (it was the first time they collaborated with a robotic system), this guideline has not been implemented.
OM.CE.14	Inform the operator about the collaboration mode change (e.g. from automatic to collaborative);	As for OM.CE.9.

Finally, the last consideration concerns the relationship between cognitive and physical ergonomics. As for other assistance systems in manufacturing requiring physical interaction between the operator and a device, improper or erroneous use of collaborative robotic systems could be counter-productive from the point of view of biomechanical loads. As a consequence, the implementation of the proposed guidelines should always consider the potential (negative) effects on physical ergonomics. Nevertheless, referring to the experimental case study, the new actions that are introduced by implementing the guidelines (e.g. the rising of the shoulder related to the gesture recognition used for human-robot communication) are neglectable from the perspective of biomechanical loads.

5. Conclusions

a. Conclusions

This work refers to human factors in industrial HRI. The study aimed to define and experimentally validate a set of design guidelines related to cognitive ergonomics in CASs. Results confirmed the hypothesis and are primarily in accordance with previous literature. Therefore, the proposed research questions have been addressed.

In particular, multiple design principles (the guidelines) to be applied when designing or setting a CAS according to cognitive ergonomics have been developed as generic as possible by analyzing the scientific literature. A laboratory case study has been used for the evaluation of such guidelines. Multiple qualitative and quantitative data have been acquired and analyzed. The operator's (positive or negative) response to the manipulation of the features and parameters associated with these design principles has been tested by using different cognitive variables and related risk factors (i.e., trust, usability, frustration, perceived enjoyment, acceptance, stress, and cognitive workload). Finally, the impact of such guidelines on assembly performance has been evaluated by analyzing the trend of critical events (i.e., assembly errors, near misses, clarification requests).

As expected, operators' experience and assembly performance improved with the sequential implementation of the guidelines. According to the experimental outcomes, it is supposed that the following measures have been appreciated by the participants: a better synchronization with the robot operations, a higher robot autonomy, greater control on the system, better awareness about workstation elements, better awareness about the robotic systems state.

These achieved results can support companies (especially SMEs) in implementing human-centered CASs. The proposed guidelines will be helpful for technicians with expertise in manufacturing systems and/or collaborative robotics but without knowledge about cognitive risk factors. Their use will help them in overcoming technological barriers and in developing more comfortable, safe, and efficient CASs. These achievements perfectly fit with the larger goals of Industry 4.0 in terms of social and economic sustainability. Finally, results can be utilized as well-structured starting points for further developments of a more extensive European-wide technical documentation regarding the psychosocial requirements for industrial collaborative systems.

b. Limitations and future works

Following, the main limitations of this work are presented.

Firstly, the number of participants was limited (14 people) and not homogenous in terms of gender (12 males and 2 females). Even if all the participants did not have previous experience with collaborative robots and had minimal experience in manufacturing operations, their background was quite different. They can be classified into two groups of the same size: people with industrial backgrounds and people with non-industrial backgrounds. This condition may influence the robustness of the results. In addition, it is possible that not randomizing the scenarios would have influenced the results as well. Even though participants had the opportunity to learn the assembly sequence of the cylinder in the training workstation, the unfolding of the experiment would allow them to familiarize themselves with the robotic system and thus influence the results. This could affect scenario duration scores in particular.

Furthermore, the experiment referred to a collaboration with a low-payload collaborative robotic system for the common assembly of a small workpiece. This is a specific condition that aims to reproduce a common, but not unique, industrial HRC. Results may change by implementing the proposed guidelines in a different CAS (i.e., using a medium-size collaborative robot or assembling heavy components).

Finally, since it was not possible to test all the developed guidelines, future studies should also integrate them to have a more comprehensive evaluation. In addition, the mutual relationships between all the proposed guidelines should be identified and quantified by considering main cognitive variables. In fact, this work did not analyze the hierarchical relationships between the various guidelines, as well as possible inconsistencies in their implementation. This is a preliminary work and the guidelines will evolve according to the results of further studies. At the moment, the choice of the most suitable solution is left to the designer. Future works should focus more also on these aspects.

According to these limitations, future studies should deepen the study of the effectiveness of the proposed guidelines in a wider way. This will require the use of a larger and more homogeneous focus group and the development and evaluation of multiple case studies related to various conditions of HRC in assembly (i.e. by using different sizes of robots and testing different tasks). This will be fundamental to gain more knowledge about the operator's wellbeing and assembly performance in the design of CASs from the cognitive perspective.

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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