Journal on Multimodal User Interfaces
https://doi.org/10.1007/s12193-024-00444-x

ORIGINAL PAPER

# Design and testing of (A)MICO: a multimodal feedback system to facilitate the interaction between cobot and human operator

**Carla Dei**[1] · **Matteo Meregalli Falerni**[2] · **Turgut Cilsal**[2] · **Davide Felice Redaelli**[2] · **Matteo Lavit Nicora**[2] · **Mattia Chiappini**[1] · **Fabio Alexander Storm**[1] · **Matteo Malosio**[2]

Received: 8 March 2024 / Accepted: 4 November 2024

**Abstract**
The present work describes the design, development and testing of a multimodal feedback system, named (A)MICO, with visual and acoustic feedback designed to facilitate the interaction of workers with collaborative robots (cobots) in production lines. The feedback is designed to make the human operator more aware of the cobot's ongoing and future activities, and therefore gain more control over the situation. The ultimate goal is to obtain a new intuitive mode for transferring information through the combination of lights and sounds, not only to facilitate the flow of communication from the cobot to the operator, but also to make the interaction more accessible to neurodivergent groups, such as people with autism spectrum disorders. The design process focused on the evaluation of the human–robot interaction to select the situations where additional information is needed, and which is the best way to transfer messages as intuitively as possible. Potential end-users were actively involved during all stages of the design and development process. Five volunteers with high functioning autism participated in a preliminary co-design to identify the issues related to the interaction with the cobot and the logic of the multimodal signals. Then, to assess the system's adaptability to several needs and the level of usability in providing information, validation tests were carried out involving a wider group of participants with ASD. The results suggest that the adoption of a multimodal communication strategy can be useful for making the workplace accessible and improving the well-being of all workers.

**Keywords** Multimodal feedback · Inclusive workplace · Human robot interaction · Collaborative robotics

## 1 Introduction

The Fourth Industrial Revolution, the so-called "Industry 4.0", is characterized by a progressive digitalization of the manufacturing process due to the new developed technologies. The socio-cultural themes promoted by Industry 4.0 have been further developed by the successive Industry 5.0, which specifically puts research and innovation at the service of the transition to a sustainable, human-centric and resilient European industry. In this framework, collaborative robots, also known as cobots, term coined by Prof. Brent Gillespie, started to be gradually adopted in production lines. The first collaborative robot was invented by Michael Peshkin and J. Edward Colgate in 1997, bringing out the innovative concept of a machine that interacts directly with the worker [1].

✉ Fabio Alexander Storm
fabio.storm@lanostrafamiglia.it

Carla Dei
carla.dei@lanostrafamiglia.it

Matteo Meregalli Falerni
matteomeregallifalerni@gmail.com

Turgut Cilsal
turgutcilsal@gmail.com

Davide Felice Redaelli
davidefelice.redaelli@gmail.com

Matteo Lavit Nicora
matteo.lavit@stiima.cnr.it

Mattia Chiappini
mattia.chiappini@lanostrafamiglia.it

Matteo Malosio
matteo.malosio@cnr.it

[1] Scientific Institute, IRCCS Eugenio Medea, Via Don Luigi Monza 20, , 23842 Bosisio Parini, LC, Italy

[2] National Research Council of Italy, STIIMA-CNR, Via Gaetano Previati 1/E, 23900 Lecco, Italy

Cobots are machines that work side by side with the operator sharing the same workstation and tasks, without a clear separation of space through safety guards and fences [2].

With the introduction of cobots, the traditional human–robot interaction (HRI) has changed according to the new role of the machines which interact directly with the operator. Starting from this assumption, several studies investigated this new type of HRI and the new opportunities and challenges related to it.

The integration of collaborative robots in manufacturing, which is the framework of the present study, allows an improved efficiency and complexity of the assembly process leveraging the precision of the machines. To reduce worker fatigue, tasks requiring repetitive actions or moving heavy objects are assigned to the cobot, which becomes a complementary element to humans [3].

However, despite its several benefits related to productivity, this new type of interaction can be a potential source of stress and negatively influence the general well-being of the worker [2, 4, 5].

Communication is of great importance in human–robot interaction, as also highlighted by several scales developed to analyse the level of anxiety towards robots, the process and the factors involved [6]. Robots should be designed with intuitive communication and cooperation modalities for human operators. Sciutti et al. describe this process as "humanization" of human–robot interaction [7], which in this context does not refer to the choice of an anthropomorphic appearance, but to the development of a code for mutual understanding between the two agents. This aspect acquires a greater importance especially when designing accessible robotic systems.

Indeed, the anthropocentric organisation promoted by Industry 5.0 and driven by technological innovations, plays a crucial role in the organisation of work, leading to several changes including the criteria for hiring workers. According to this, the new generation of assistive technologies, implemented in production systems, offers appropriate and customisable solutions to provide assistance during the task, representing a valuable aid to improve the productivity of the human operator but, above all, to offer job opportunities to people with disabilities or special needs [8]. Johnston et al. [9] describe assistive technologies as items adopted for maintaining or improving functional capability for an individual with disabilities. Indeed, the innovative and intelligent solutions, being flexible and adaptable, can compensate for several cognitive or physical worker deficits [10].

As a general guideline, the human–robot interaction should be designed to be easier and more human-friendly [11] to reduce the fear of machines, and, furthermore, be flexible and adaptable to encourage the work inclusion of people with physical impairments or neurodiversity who find this type of technology a valuable aid [12]. The concept of 'neurodiversity', coined and diffused by the sociologist Judy Singer in the 1990s, defined some developmental disorders as normal variations in brain function and not as deficits. Nowadays, this term refers to a broad group of users, including those with neurological or developmental conditions such as attention-deficit/hyperactivity disorder (ADHD), those with learning disabilities such as dyslexia and those with autism spectrum disorders (ASD). In this framework, the term neurotypical refers to users whose brain functioning and development is considered the norm by the general population.

Neurodivergent people face several difficulties in finding and maintaining their job due to the lack of support, also caused by the overall organization of resources and environmental factors such as stigma [13]. Research focusing on solutions facilitating the employment of neurodivergent workers, such as those with ASD [14] may provide employers with the appropriate tools and knowledge on inclusive recruitment [15], reducing barriers to employment.

Creating accessible environments where everyone can join in and have the same experience is one of the main concepts promoted by the design approach called 'Design for All'. This term was introduced in 2004 to indicate "design for human diversity, social inclusion and equality" [16] and to emphasise the importance of guaranteeing the dignity of all users, overcoming the traditional concept of architectural barriers focused only on physical impairments. The concept of 'Design for All' aims to design smart solutions that are well harmonised with their surroundings and usable by all indiscriminately [17].

Starting from these considerations and the actual socio-cultural context, the present study aims to design a solution to make the interaction between collaborative robots and operators more intuitive and accessible for all neurotypical and neurodivergent operators. This aspect suggests the need to simplify the collaboration between these two entities, which is both the goal and the basis of any cobot system [18]. Indeed, the communication between human and robot should be configured as a bi-directional channel to result in a positive user experience. With the spread of innovative technologies, modern cobots have begun to be implemented with software and sensor systems to provide them with cognitive skills to achieve a more natural HRI [19]. In addition, in recent years, the integration of tracking systems into cobots provides a solution for assessing the physical and psychological state of the worker [20].

However, there is still a gap in mode of how cobots communicate with workers. Indeed, current human–robot interaction models show that operators can interact with machines through different interfaces (e.g. displays, buttons), while machines are not equally equipped to communicate explicitly with humans [21].

For this reason, the present research specifically focuses on the modality of transmission of information from a collaborative robot to a human worker.

To achieve this purpose, we developed a multimodal feedback system, composed of a combination of visual and acoustic signals, to reinforce and integrate the information transmitted by the cobot regarding the activity in progress. The resulting user experience (UX) is based on a multimodal interaction, which refers to the availability of multiple communication channels in the HRI. Instead of having a single input/output transmission mode, multimodal interaction provides a range of choices that can be combined, allowing to design a customized solution [22, 23].

To design a positive experience with the cobot, the information must be conveyed as intuitively and simply as possible, so that it can be understood by everyone, reducing the stress and anxiety due to not being in control over the situation. According to this, several studies confirmed that visual and auditory signals are the most immediate modalities for individuals to interact with robots [24]. In addition, making the cobot activity more transparent allows a faster and more efficient collaboration [25]. This aspect is also confirmed by investigating human robot interaction in different fields (e.g. manufacturing/industries, military, healthcare).

Throughout the design and development process, the researchers worked with a group of potential end-users composed of people with ASD, chosen considering their communication problems and constant need for specific and clear information. Indeed, several studies explain how the integration of smart technologies, in the production system, can be a valuable solution to promote the work inclusion of people with ASD [26], improving their autonomy in decision-making and time management [27].

The design and development process were organised in sequential phases: co-design involving users with high-functioning autism, definition of the physical mock-up where signals were integrated, definition of an experimental protocol and the final testing phase involving ASD participants. Design for All principles guided the entire research, aiming to obtain a new communication strategy that could represent a valuable aid in improving the well-being and productivity for all workers. Furthermore, considering that many workplaces are not designed with accessibility functions [12], the developed solution must be able to be adapted to a pre-existing system and its feedback should be customisable, making work activities more human-friendly and accessible to all. The ultimate goal of this paper is to present the design process and testing of a new intuitive mode for transferring information through the combination of lights and sounds, to facilitate the flow of communication from cobot to operator and make workplaces more accessible to neurodivergent people.

## 2 Related works

### 2.1 Human cobot interaction

The traditional conception of industrial robots referred to systems working within fences, separated for safety reasons from the areas where humans operate. With the aim of combining the strengths of machines and humans, the development of innovative technologies led to the creation of robots working directly and safely with users [28]. In the framework of Industry 4.0 and 5.0, cobots started to be widely adopted in production lines. The physical contact between humans and cobots performing a task together, sharing the same workstation, is what defines their activity a ‘collaboration’. According to this, also new environmental factors (e.g. cobot size) may occur and change the user’s perception of HRI [29].

In addition, the new work organisation, derived by the adoption of cobots, has led to a change in the way of communicating and interacting with these machines: facilitating communication and making cobot activities understandable plays a huge role to allow the diffusion of this technology in production lines [30]. This framework provides the cobot with a new role as a “teammate” rather than a “tool” [31].

According to this, the present study focused on the interaction defined as collaboration and the emerged importance of an integrated communication system that can transfer information quickly and clearly. To reach an optimal solution, the information should be transferred through several communication channels. Designing a multimodal communication strategy means that the information is transmitted through different channels, also simultaneously: in this way a user with impairment can choose the mode of transmitting information most suitable to its own needs, without reducing the functionality of the system [12, 32]. The availability of several channels also allows the user to choose one or more of them according to personal needs. Several studies describe interesting examples of HRI enriched by multimodal communication systems that, by adopting different channels such as gesture recognition, voice control, and haptic feedback, aim to achieve a more affective interaction with humans [33]. Often two or more types of feedback are combined simultaneously to reinforce the meaning of the information transmitted.

The literature suggests that studies related to the integration of technology to promote communication flow between robot and human, although aimed at achieving mutual understanding between these two agents, focus more on the robot’s ability to understand the user’s state [34]. Moreover, the transmitted information rarely informs about failures, robot errors and misunderstandings. As general rule, the multimodal feedback system must transfer the right amount of information, without adding complexity to the task and increasing the user’s workload [33].

A well-designed multimodal feedback code can have a great impact on the work experience and open new opportunities for people with neurodiversity, making the environment more accessible [35]. Autism spectrum disorder is a neurodevelopmental disorder characterized by repetitive behaviours and several deficits in social interaction [36, 37]. Several studies describe how the work experience of people with ASD can be made more complex by noisy environments, multiple perceptual stimuli, lack of contextual understanding and unpredictable social relationships [38].

The lack of support, also caused by the overall organization of resources and environmental factors, contributes to increase the difficulties for people with ASD to find and maintain a job [13]. Based on this, the present study involves a group of users with ASD in the design process in order to provide a solution to address the most common problems related to collaborative tasks performed using a cobot.

## 2.2 State of the art: signalling code

The role of cobots in the workplace is gradually changing, implying new ways of communication, and the availability of new technologies lays the foundation for making interaction with operators more flexible and natural [24]. Assuming that there must be a mutual understanding between humans and cobots, the present study focuses specifically on the flow of information transmitted by the latter.

Among the various strategies proposed, the adoption of multiple sensory channels seems to be the most valuable solution for adapting feedback to a wide range of users. Each channel of communication can be used alone or combined with others [39]. Identifying the type of information to be transferred is also a crucial element to consider when designing a new communication mode applied to HRI [40, 41].

Villani et al. have designed a wristband to make the worker more aware of cobot’s activity through haptic feedback. This kind of feedback was also compared and combined to light signals to identify which is the best solution to transfer information about cobot activities. The study identifies that the perception of haptic feedback, associated with the state of the cobot, can be a valuable method to transfer information without the addition of other signals [42].

Another approach was proposed by Höcherl et al. that designed a system composed by a led ring and a sound module, placed on the cobot’s arm, and two displays integrated in the worktable. The information is distributed in these channels to avoid any kind of distraction: LED lights convey information about the status and operation mode of the cobot, while displays show more detailed information. A sound signalling error is emitted when there is a failure and another acoustic signal is emitted when the cobot reaches its limits [43].

Other studies, including that of Fernandez et al., focused specifically on the potential of visual feedback to transfer information about the movement of the cobot [44, 45]. The visual and light signals can be designed, in terms of colour and frequency, to transfer a wide range of information on cobot activity [46]. Especially the use of coloured visual feedback is considered a valid strategy to transfer information in an even more intuitive way [44, 47], but it has to be designed according to the cultural context of the final application.

The information conveyed by the visual signal can be reinforced by the integration of an acoustic signal that helps user to better understand of the robot’s behaviour. An HRI implemented with this type of solution can influence positively the human perception of the experience [48].

Despite few guidelines or standards that guide their design [46], visual and auditory signals are the most immediate mode for individuals to interact with robots [24]. To achieve an optimal result, the feedback system must be designed considering all environmental factors (e.g. noises, light, obstacles). For example, Gwilt et al. did not to implement, sound alerts because of the noisy factory setting, although their introduction was suggested by several participants involved in the study [41]. Each signal, both visual and acoustic, must be clearly understood by the operator, without being an element of potential misunderstanding between human and cobot.

A HRI implemented by a well-designed feedback system improves the wellbeing of the worker augmenting control over the situation and the perception of the collaborative robot [49]. This scenario also opens up new frontiers in the field of labour inclusion.

# 3 Study setting

The present study was developed within the research activities of the European project Mindbot (https://www.mindbot.eu/). The main goal of Mindbot was to design human–robot interaction promoting mental health in production lines, by adopting collaborative robots that can adapt to user’s needs, both physical and mental, and also make the workplace more accessible to neurodivergent workers.

During the research activities of the project, a laboratory setting (Fig. 1) was setup where both neurotypical and high functioning autism individuals could test a pick and place collaborative scenario simulating a week of work, with daily shifts of 3.5 h [50]. The workstation was composed of two tables, arranged in an L-shape: one for the cobot and the other for the human operator. The cobot’s working area was divided into areas where different parts had to be placed to be recognized and then assembled correctly. Operator’s tasks included also refilling the cobot table when there were no more parts to assembly. If the operator forgot to refill the

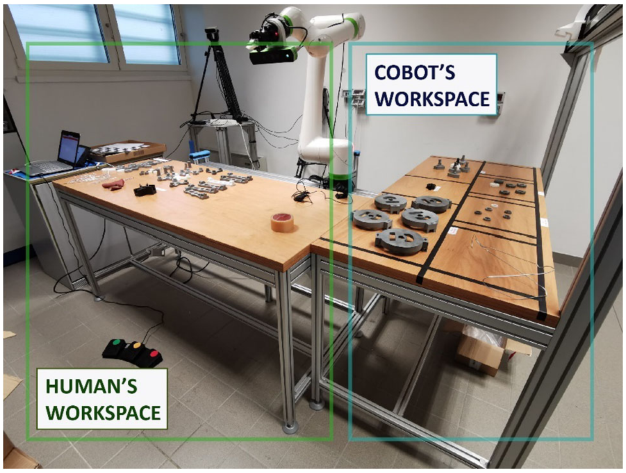

**Fig. 1** Lab setting where participants performed the pick and place task with the collaborative robot

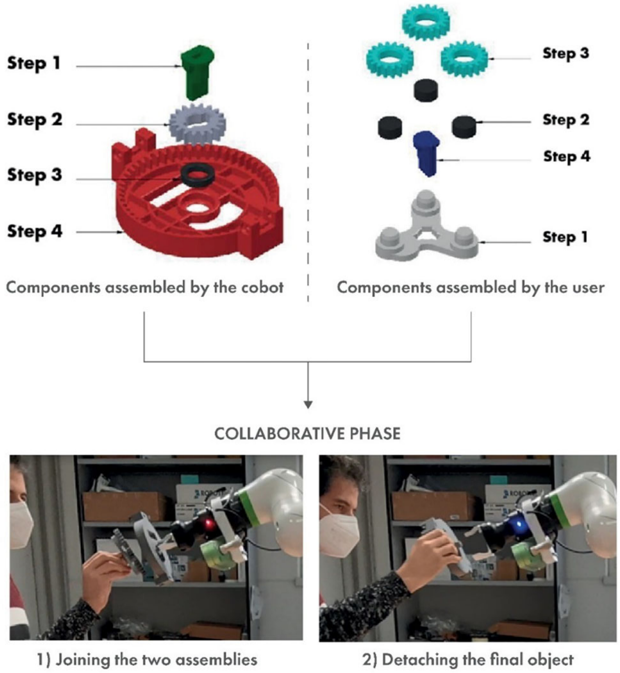

**Fig. 2** Collaborative task

cobot table or did not place enough pieces in the correct spaces, the cobot stopped. To avoid this situation, before the start of the working week, all participants were involved in a quick training session to be briefed on the collaborative task, including the instruction for managing and properly position the parts to be assembled by the cobot. Instead, the parts on the human operator's worktable could be arranged freely according to its preferences.

Figure 2 shows the components assembled by the cobot and the human operator, and the collaborative phase in which the latter joins the two assemblies and detaches the final object from the gripper.

The design process performed in the present study used this collaborative scenario and task as a pilot reference. The ultimate goal is the integration of an intuitive interface that allows the user to customise feedback according to any cobot and collaborative task.

## 4 Requirements

The aim of this project was to create a plug-in component of the cobot system facilitating the information flow from the latter to the worker. The user experience in the collaborative scenario, described in Sect. 3, suggested the preliminary requirements that the device should have, setting the basis for the next stages of the development process.

First of all, considering the aim of the project, the provided information should be supportive without disturbing or annoying the worker.

In addition, the device must be flexible enough to provide programmable multimodal feedback that can be configured according to requirements and the information to be conveyed. The multimodal feedback should be able to provide at least auditory and/or visual signals, also to satisfy specific sensory needs of different users. In addition, all designed feedback also needs to comply with specific ISO Norms (see Sect. 5.2).

The size of the device must allow for sufficient visibility but with a limited footprint, so that it can be easily integrated into a production scenario with collaborative robots.

Another important environmental aspect to consider in the design process is the positioning of the feedback source, which has an impact on the overall user experience. Indeed, the information transmitted through the multimodal feedback, must be available to the worker when clarification on the task is needed, but without being a source of distraction for the rest of the time.

## 5 Prototype

The first prototype of the device, named (A)MICO (acronym for "A Multimodal device to improve inclusive Interaction between Cobot and Operator"), was designed considering the issues emerged from literature and respecting the requirements described above.

In addition, a general benchmark research was performed considering the most common cobots adopted in today's production lines to identify which visual and acoustic feedback are implemented,

The benchmark was carried out by selecting mainly the products available on the official websites of the most famous robot brands and also taking into account, as additional information, the prototypes described in scientific works [49, 51]. The results suggest that the three major types of information which can be conveyed by light are:

1. Cobot status (e.g. white = standby/green = production in progress/yellow = programming/red = stop).
2. Position of the user in the working zone of the cobot (e.g. green = worker is in a safe zone/yellow = worker has to be careful because in proximity to the cobot/red = cobot stops because worker is too close to the cobot).
3. Cobot working mode (e.g. green flashing = manual guided mode/green = collaborative mode/led turn off = industrial mode/blue = collision or restart/red = error).

As for colour for light signals, there is no recommended range; it depends on the specific collaborative task and cultural background. Regarding the positioning of source of visual feedback, most of the commercial cobots usually integrate it on their base or in the zone near the gripper.

Although light-signal integration, as confirmed by the benchmark, is the most adopted strategy in cobot communication systems, there are still few guidelines or standardised tips that guide their design [46].

As a result, many signals are not intuitive and require significant mental effort to be memorized. Learning the code, especially when it is not perceived as intuitive, can become very difficult, especially for a neurodivergent user. It is mandatory that the reporting code does not add mental effort to that required by the work task. Visual information can be combined with acoustic feedback to reinforce the meaning of the transferred message. Indeed, acoustic feedback acquires an additional impact when combined to the visual one [52] and vice-versa.

As for the visual signals, also acoustic feedback can be modified to share different information in accessible ways according to user needs [53].

### 5.1 Product design

The prototype has a cylindrical shape with a limited footprint, with overall dimensions equal to 20 cm Height × 25 cm Diameter, so that it can be easily placed in the workstation area, without affecting the clarity of the information transmitted on the curved surface. The sizing of the components is studied taking into consideration the technical elements necessary for operation and the context of use (e.g. workplace with reduced available space).

The aesthetic of the device is inspired by that of the signal towers that are usually placed in industrial settings. In addition, the rounded shape recalls the lines of the cobot's arm joints and makes the object more emotional and affective. Moreover, this shape could allow the device to be fixed along the robotic arm, embraced to it, taking advantage of its hollow cylindrical shape.

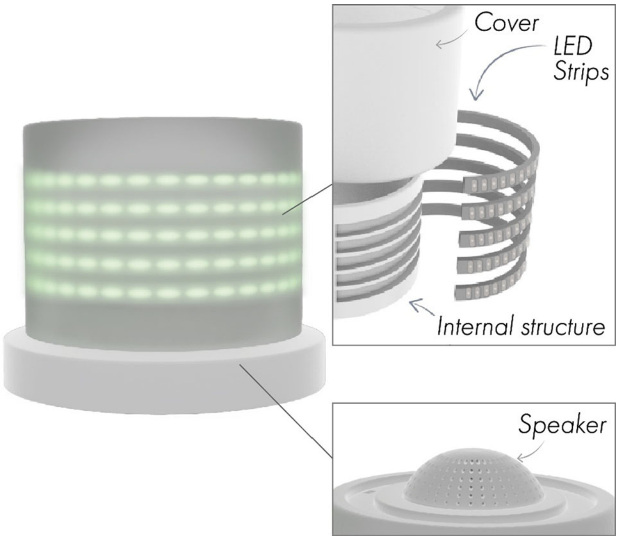

**Fig. 3** Design and internal structure of the preliminary prototype of (A)MICO

(A)MICO is composed of a base with a speaker, on which the light-emitting tower is fixed. The tower itself is a hollow cylinder, covered by an opaline material, with grooves for attaching five LED strips, as shown in Fig. 3. The parallel LED strips are fixed at the central body, with a distance around 1.5 cm from the rubber cover, in order to obtain a good trade-off between the ability of demonstrating clear figures and the need of not disturbing the worker.

All components are 3D printed in PLA and assembled, except for the element covering the LEDs, made of semi-matt rubber to provide a soft light feeling.

### 5.2 Feedback system

The multimodal feedback is composed by a combination of visual and acoustic signals. The former are coloured lights in the form of 2D graphic patterns, to be accessible also to colour-blind users, and are emitted by LED strips, placed in a matrix, integrated in the curved surface of the device. The LED matrix allows the creation of coloured luminous patterns on the cylindrical surface of the device, like in a standard led matrix panel. The pattern is replicated across the entire surface, so that it is always visible to the operator when transmitting information.

The resulting user experience is natural and intuitive and does not force the worker to do additional movements to see the feedback. In order to reinforce the communication strategy, and to meet the needs of specific users, acoustic signals are also added. They are emitted by a speaker embedded in the base of the device, to transmit information clearly but without annoying the user. The circular element with the LED strips, due to its concavity, is used as a resonance chamber.

A distinguishing feature of (A)MICO is the compact mode of transferring visual and acoustic feedback. Considering that the sounds are emitted by the speaker integrated in the base on which the cylindrical surface emitting the visual signals is fixed, this means that the user gets the information from one compact source. The strategy behind this feedback system is to associate each visual signal with an acoustic one that transfers the same information. The signals, which consist of a sound and a graphic pattern, are transmitted simultaneously, reinforcing the mutual value and making the message more understandable.

Both visual and acoustic feedback were also designed considering environmental factors of potential work settings, such as light condition and background noise. They can be adjusted in intensity or deactivated.

The design and development process of the feedback system also considered that the visual and acoustic signals emitted by the machines in an industrial setting are standardized in ISO Norms: Visual Danger Signals (ISO 11428 [54] and 11,429 [55]) and Ergonomics (ISO 7331 2005, Danger signals for public and work areas, Auditory danger signals [56]). However, these documents do not provide specific guidelines for designing an effective and accessible human–robot interaction [57].

### 5.3 Software architecture

The (A)MICO prototype is connected to the robot controller through a Bluetooth connection and the software interfacing with the device occurs via ROS, the Robot Operating System [58]. This guarantees a potentially very flexible and multi-platform use, as more and more robot manufacturers develop controllers compatible with the ROS communication middleware.

The device is controlled via dedicated firmware running on an Arduino Nano board. This architecture allows to translate the actions of the cobot into lighting and acoustic patterns in real time.

## 6 Preliminary co-design

To identify the type of information the device should transfer and its modality, a preliminary co-design session was organized.

The main goal of this phase was to define the best combination of visual and acoustic feedback that can support the operator during the collaborative task, especially when there is a risk of misunderstanding with the cobot or situation that can be a potential source of stress.

### 6.1 Participants and recruitment

The present research activity was conducted according to the guidelines of the Declaration of Helsinki and approval by the Ethics Committee of Istituto di Ricovero e Cura a Carattere Scientifico Eugenio Medea (protocol code N. 19/20CE of 20 April 2020) was obtained. All participants received an information sheet about the aims and procedures of the study. Before starting the data collection, they were asked to sign an informed consent, including consent to the processing of personal data.

Five users with high functioning autism (1 female and 4 males) were involved in the co-design process for creating visual and acoustic feedback to be integrated in the physical device (A)MICO. Participants were recruited from among those who had already performed the collaborative task with the cobot, without (A)MICO, for five days as mentioned in Sect. 3.

### 6.2 Methods

To collect data about the type of feedback to integrate in (A)MICO, the participants were asked to complete individually an interactive questionnaire using a tablet provided by the researchers. The present activity was usually performed after the last working day with the cobot, allowing participants to have a complete overview of the experience resulting from the interaction with the cobot.

After the introduction page, the next four pages displayed videos about different combinations of visual and acoustic feedback designed for situations identified as potential sources of stress and anxiety (Fig. 4). This list of situations was proposed by a group of researchers who observed participants working during the collaborative task proposed in the Mindbot project, described in Sect. 3.

The three situations identified as critical and needed to be integrated with further explicit information, are the following:

1. The cobot stops because an error has occurred requiring the manual intervention on the system (e.g. the cobot software crashes and needs to be restarted);
2. The cobot stops because the piece is not correctly positioned on the worktable, and it does not recognize/see it (*searching phase*);
3. The cobot finds the piece (after the *searching phase*)

For situation 1 (error) there were three videos with the same visual feedback but different sound proposals to choose from. The same layout was used for the moment in which the cobot finds the part. Finally, for the situation when the cobot is searching for the part, in addition to the sound feedback,

**Fig. 4** Screenshots of the interactive questionnaire. For each situation listed above, the researchers designed a combination of visual and auditory feedback and the participant had to indicate which one was best at conveying the information

the participant could choose the colour of the visual feedback between orange and green.

The proposed visual feedback was designed considering the information emerged from the literature and from benchmarking.

All the information that emerged was adopted as guidelines for designing the visual and acoustic feedback to be implemented in the (A)MICO physical device.

## 7 Preliminary co-design results

After completing the questionnaire, participants expressed their need for additional feedback informing about the overall workflow status. Indeed, especially for people with ASD, having frequent feedback on the ongoing work is a valuable way for reducing stress and for having a better awareness of time passing.

Figure 5 summarises the visual and acoustic feedback designed considering the information that emerged in the co-design. For the situation in which the cobot stops because of a system error, the feedback chosen was composed of a red "X" signal blinking with a sound that recalls the idea of an alert. When the cobot temporarily stops because it cannot find pieces, the feedback chosen was composed of blinking orange arrows pointing to the worktable, with a sound effect that recalls the idea of suspense. After the worker places correctly the pieces, the cobot restarts and all led blink in green as a symbol of confirmation, together with an upbeat sound [59]. Finally, to inform about the general workflow, rainbow shades appear on the surface of (A)MICO together with a positive sound reinforcing the idea of the achieved goal. The logic behind this feedback can be customised according to the task: in our case study, we decided to activate it every 10 completed assemblies. Video files related to the combination of visual and acoustic feedback are available as supplementary material.

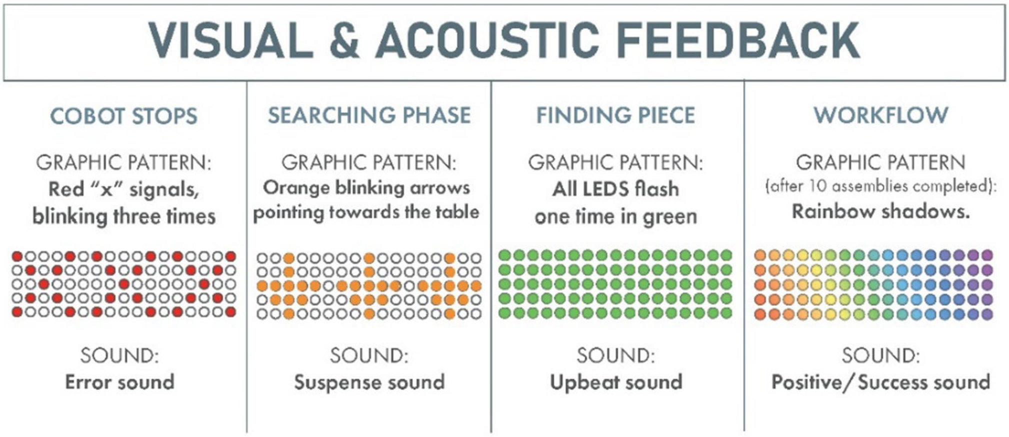

**Fig. 5** Overview of the visual and acoustic feedback chosen by the ASD participants involved in the co-design

## 8 Testing

To evaluate the potential of the designed feedback system, twelve participants with ASD (2 females and 10 males) were involved in the experimental tests. Participants had to work on the same collaborative pick and place scenario described above. All ASD participants recruited in this phase never interacted with a collaborative robot before.

The test organised in the laboratory was composed of two sequential phases: a practical trial with the cobot and a semi-structured interview. As a first step, after a quick explanation of the task performed by one of the researchers, each participant was invited to work with the cobot for 5–7 min to become familiar with the activity. Then, for the same amount of time, they were asked to perform the task with the help of the multimodal feedback emitted by (A)MICO, which was positioned on a table in front of the human operator's workstation (Fig. 6). The researcher did not provide any explanation about the significance of the feedback but was always available to the participants in case of doubts about the task.

After this phase, each participant was individually involved in a semi-structured interview performed by one of the researchers. All participants had social skills that enabled them to express their thoughts and actively interact with the researcher.

The semi-structured interviews lasted around 15 min per participant and aimed to investigate the quality of the experience, the comprehension of the feedback system and the learning level of the task, through direct questions such as:

(1) In your opinion, which is the function of (A)MICO?
(2) Did you prefer working with (A)MICO or without it?
(3) Did the visual/acoustic feedback disturb you?
(4) Was the information given by (A)MICO intuitive?
(5) Where would you think the feedback source, such as the device (A)MICO), should be positioned?

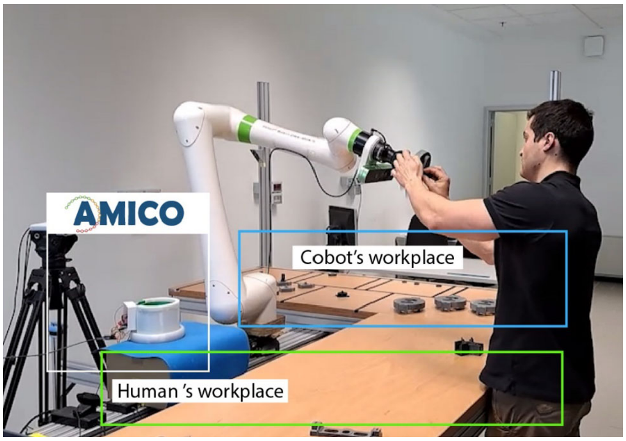

**Fig. 6** Lab. setting implemented with (A)MICO. During the task, the participant and the cobot assemble the pieces shown in Fig. 2, individually at their workstations until the collaboration phase. The participant only enters the area of the cobot's workstation if it needs to be refilled with pieces

The participant was shown a quick video of each feedback before being asked about its meaning. This section of the interview played a crucial role in identifying whether the chosen visual and acoustic signals were sufficiently representative of the message they conveyed. The full list of questions provided during the semi-structured interview are available as supplementary material.

## 9 Testing results

The subjective data collected from the semi-structured interviews can be divided into three thematic areas: perception of the device, understanding of the messages conveyed by the multimodal feedback system and general opinion on the user experience. All sessions were recorded, with the consent of the participants, to facilitate transcription and organisation

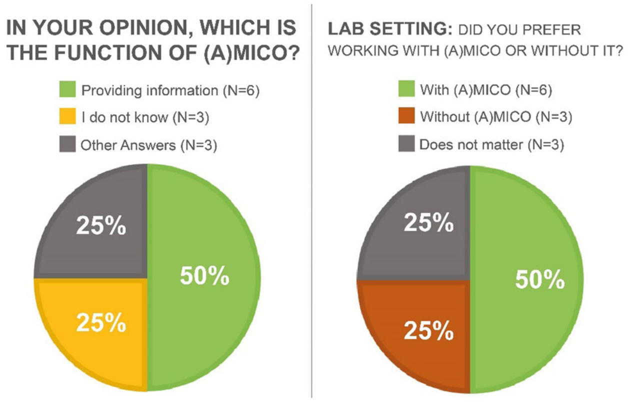

**Fig. 7** Overview of the answers related to the perception of the physical device (A)MICO emitting multimodal signal

of the results. Each participant was classified with a personal code composed by the letter "P" (acronym for "participant") followed by a serial number from 01 to 12.

## 9.1 Perception of the device

All feedback was transmitted by the physical device (A)MICO, which was placed on the table in front of the operator, near the cobot, as shown in Fig. 6. As the pie graphs in the Fig. 7 show, half of the participants understood the general meaning of the function of the device. Answers gathered in the macro category "Providing information" also included those who had partially understood the function of the device, such as P12 who said *"…to work in the factory. It means that it is ready"*. It was decided to keep this category very general to emphasize that participants understood that (A)MICO transfers some information.

Among the remaining answers, someone stated that they did not know what the function of the device was, classified as 'don't know'.

Regarding the potential risk of (A)MICO being a source of noise, no one seemed to be bothered by its presence. Indeed, as confirmed by the answers to the question on the preference to work with or without the device (Fig. 7), the participants who answered that they preferred to work without (A)MICO, explained that they did not pay attention to any kind of feedback and, consequently, were not annoyed by it.

## 9.2 Understanding of the feedback

The level of feedback comprehension, investigated in the second part of the semi-structured interviews, played a crucial role in the development of the feedback system. For each combination of visual and acoustic signals experienced by the participant during the practical part of the test, a video was played, asking what kind of message it was conveying (Fig. 8).

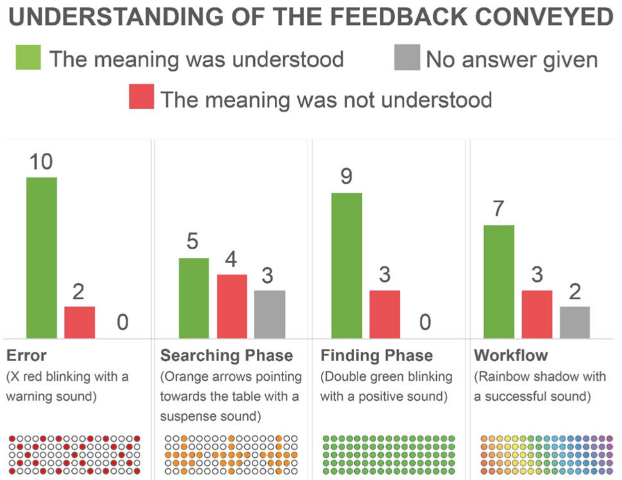

**Fig. 8** Overview of the answers given by the participants regarding the understanding of the message conveyed by the signals

The feedback designed to notify the presence of an error emerged as the most intuitive: almost all participants (N = 10) understood that it referred to a negative situation. Only two participants misunderstood the signal, identifying it as a positive message.

The two feedback signals on the right of Fig. 8, regarding the finding phase and the workflow, were mainly intended as indicators of a general positive situation, without identifying the specific meaning of the message. Considering that users had a short time to work with the cobot, they were not expected to specifically identify the two meanings of the feedback but having understood that the message conveyed was positive was considered a good outcome.

Regarding the former, only three participants did not understand the meaning of the signal, providing not pertinent answers – "*something shiny*", "*phone notification*", "*buttons*".

Among the answers given for feedback on the workflow, apart from the correct ones and those of the two participants (P04 and P05) who stated that they did not understand the meaning of the signal, three participants (P01, P02 and P07) gave other different interpretations – "*something shiny*", "*sound similar to video games*", "*buttons*".

Instead, feedback related to the searching phase (second signal in Fig. 8) turned out not to be intuitive enough to be understood. Indeed, most of the participants didn't understand which message was conveyed by it – "*It means GO!*", "*Cobot is going down*", "*Notice that the robot was looking down*"- giving a personal interpretation of the signal.

### 9.3 General opinion on user experience

During the semi-structured interviews, several considerations emerged on the user experience, highlighting the wide heterogeneity of sensitivities [60, 61] of users with ASD.

Some interesting views emerged on the potential improvement of *acoustic* signals: two participants (P03 and P05) suggested that the message could be conveyed through words, instead of just sounds, to be more explicit – "*I would like that (A)MICO can say some words as "work done" or "work in progress…"*".

Another participant (P11) expressed the potential of acoustic signals to *keep* the workflow regular, especially when the user starts to get tired – "*If the user is tired, sound feedback helps to keep the workflow regular, providing a kind of rhythm*". No relevant considerations emerged concerning the visual patterns.

Several opinions were expressed about the positioning of the device, that during the practical trial was placed on a table in front of the user. One participant (P11) expressed disappointment with this condition – *"…the device should be in another place. The* current*positioning is a source of distraction for me. I did not look at it during work…*".

Five participants *preferred* (A)MICO to be positioned closer to them – *"I would prefer the device to be positioned close to me to see the feedback better"*-, while three others on the arm of the cobot – *"I suggest the cobot's arm because it is natural to shift attention to something is moving*"-. Two participants were happy with the current positioning of the device, while the remaining two did not provide any comments on this topic.

To better investigate feelings about the entire user experience resulting from the integration of (A)MICO, the last question asked whether participants, after understanding the meaning of the feedback, would like to have the device if they were workers interacting with cobots in production lines. What emerged largely confirms the results from Sect. 8.1 on the perception of the device, with a few exceptions (Fig. 9).

The six users (P01, P02, P05, P08, P09 and P11) who preferred working with (A)MICO already during the lab setting, gave as their main explanation that, in a real working context, having the feedback system could be a valid help to maintain concentration at work, improve productivity and know what the cobot is doing.

One (P03) of the three participants who did not know if preferring to work with (A)MICO during the task, replied that in a real work environment it would be better working with (A)MICO, due to the personal discomfort in interacting with people – "*I would like to work with (A)MICO because I prefer to interact with robots instead of people*". The other two (P06 and P10) did not respond to the question.

Among the three (P04, P07 and P12) users who stated that they did not prefer to have an (A)MICO available during the task, only one (P07) did not change his/her mind when thinking about an application in a real context – "*It is easier*" [working without].

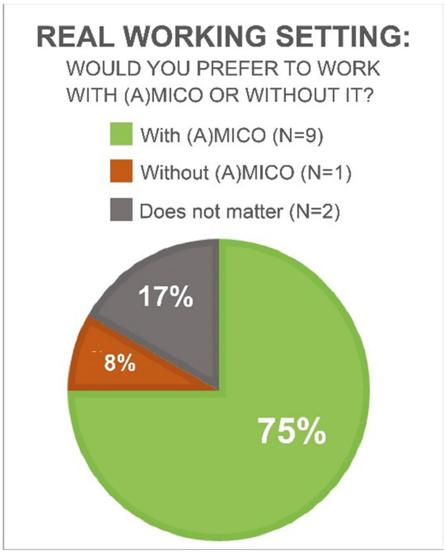

**Fig. 9** The answers given by the participants regarding the potential value of the feedback system in a real working context

## 10 Discussion

The main goal of the study was developing and testing a multimodal feedback system that can be a valuable aid for operators interacting with a collaborative robot. As declared in the introduction, the design and development process were structured following the guidelines proposed by the Design for All approach that aims to design a solutions usable by the widest possible range of users [62]. According to this, the feedback emitted by (A)MICO is designed to provide information without disturbing the human operator, improving the work experience of both neurotypical and neurodivergent users.

A group of potential final users were involved in a co-design process, which is a creative cooperation during design development in which the topic is approached from different perspectives to achieve innovative design solutions [63]. According to this, the participants recruited for the testing phase have a diagnosis of Autism Spectrum Disorders. The results obtained provide a valuable starting point for discussing the objectives achieved and the future developments of the project in terms of accessibility and social inclusion. In addition, the inclusion of users with ASD in the design process allowed to analyse the system from different perspectives and increase the acceptance of the final product [64].

## 10.1 Perception

What emerged from the interviews shows that half of participants understood the purpose of the presence of the feedback system emitted by (A)MICO correctly. This apparently negative result was not surprising because in the laboratory experiment, the idea was to provide no explanation of the device in order to assess the degree of intuitiveness of the experience. Furthermore, the participants were given a very short time to familiarize with the cobot before (A)MICO was added to the setting. This condition, due to an organizational limitation, did not allow them to become familiar with the steps of the task and the potential errors or problems related to it.

To better evaluate the results emerged, we also have to consider that participants with ASD are characterized by particular behavioural patterns [65] and reasoning processes which are more reflective than intuitive [66]. The setting of the experiment was specifically designed to test whether the feedback system is sufficiently intuitive to cope with the participants' difficulties giving them limited time to reason about the situation. Obviously, in a real work context, an explanation of the use and functions of the device would be part of its installation. Workers know the task and the sequence of the cobot's activities, but unexpected situations may occur, which in turn may increase the risk of stress: this assumption confirms the usefulness of having feedback to help identifying and managing errors in these circumstances.

Regarding the addition of (A)MICO in the setting, although the purpose of the device was not fully understood by all, its presence did not represent a source of disturbance. This was a very important result considering that ASD participants may be characterised by hypersensitivity or hyposensitivity to external stimuli [67]. Indeed, as emerged in the results, half of the participants preferred to work with (A)MICO while those who preferred to work without it were not bothered by it. Three participants did not provide any answer.

This aspect suggests a good acceptability of (A)MICO and of the feedback provided, but further studies need to be conducted, with a wider range of participants, and planning longer laboratory tests to assess the actual tolerance of the end user to sound and light. Indeed, the final system must integrate strategies to embrace the different stimulus perception modalities of the widest variety of persons [68, 69] in order to be a valuable aid in a working environment not specifically designed for this target group.

## 10.2 Understanding

The level of understanding of the messages transmitted by multisensory feedback is the core of the entire study and sets the ground for future improvements. Indeed, developing a tool that provides additional information in an intuitive way allows the operators to achieve a higher level of autonomy in the workplace [27]. The selection of participants with ASD in the test phase was also a strategic choice considering their difficulties in abstraction reasoning [70]: extracting complex information conveyed by a combination of visual and acoustic stimuli is not such an easy process, especially for this target group.

The message transmitted by the combination of flashing red X with an alarm sound was rightly understood by almost all participants (N = 10) as a sign of something negative, such as an error or malfunction. Also, regarding the feedback related to finding the component and the workflow, most participants understood the positive message conveyed by the signal. Not surprisingly, the specific meaning of both feedback was not understood, because the participants were not very familiar with the task. However, not all signals proposed have reached the goal to transmit messages in an intuitive way: the one related to the "searching phase" turned out to be the most critical to understand.

As with the other feedback, it is not surprising that the specific meaning was not always fully understood, but the problem was that most participants were very confused about the signal, both visual and acoustic. Some did not recognise the graphic pattern as an arrow, others assumed the arrow meant the cobot was looking at the worktable or that the robotic arm moved the gripper towards the table. This misunderstanding is probably also due to the fact that participants were unfamiliar with the task and did not recognize when the cobot was stopping for searching a part. What emerged suggests that the signals need to be redesigned to transmit the message more explicitly. To this end, as suggested by some participants, a clear voice message could be more direct than generic sound effects.

Some participants faced the problem that when the cobot stopped, they did not know if the cause was an internal error or just incorrect positioning of the parts, overall resulting in a considerable waste of time. To avoid this situation, the feedback, composed of orange arrows and a suspense sound, needs to be redesigned to make it more explicit.

As a general consideration, the main element of misunderstanding was that the signals were often interpreted as those emitted by a traffic light, which reflects the reflective reasoning attitude of most ASD individuals [66]. According to this, some users thought that the feedback related to the searching phase was not linked to the idea of pause but to the request of increasing the speed of task execution. In addition, various participants interpreted the meaning of the signals in association to their life experience. As an example, two of the participants are video game players and their answers were partly influenced by the logic of games.

### 10.3 General opinion

The idea was to find out whether, starting from the personal experience in the lab setting, the participant would like to have the device (A)MICO available to become more aware of the cobot activity in a real working context.

Investigating this topic was not an easy process because people with ASD have several difficulties in abstracting concepts and imagining what it might be like in another environment [70]. Furthermore, communication problems of the users contribute to make more difficult sharing their considerations and observations [71, 72].

Participants were excited to work with a collaborative robot and most of them would feel comfortable receiving the additional information transmitted by (A)MICO in a real working environment. Their responses revealed some traits of ASD, such as a sense of duty or the need to be in control of the situation [73]. One of the participants, who disliked working in the presence of multimodal signals during the laboratory task, stated the preference to have the latter available instead of dealing with human colleagues in a real work context.

However, the general positive opinions could have been influenced by the duration of the practical test, which lasted approximately 15 min. The feedback could be a valuable support to help the operator, but it should be tested over a full working shift to assess that the feedback does not actually bother.

### 10.4 Study limitations

This study was conducted with a reduced number of participants with ASD: five in the preliminary co-design process and twelve in the testing phase. Considering the purpose of the study, specific data about the profile of the ASD participants were not collected since a group of autism experts supported the researchers in recruiting the population.

Considering the main objective of achieving a feedback system accessible to all, further tests should involve users with other types of neurodiversity and neurotypical participants who were not involved in the testing activities performed. In addition, (A)MICO was tested when still in its prototyping phase, which means that some technical aspects, such as the adoption of Bluetooth connection, may be modified in future developments.

The validation tests should last more time to verify the effective tolerability and acceptance of visual and acoustic feedback. All users involved in the test had never been in contact with a collaborative robot before and were very curious about the overall situation. This led to an overexposure to stimuli, which made more difficult for people with ASD keeping their attention on the feedback given. Above all, the presence of the cobot was a main source of interest and, consequently, distraction.

The name of the device, (A)MICO, was also an element of misunderstanding because in Italian (the mother tongue of the participants) the same word means “friend”: for this reason, in some sessions it was generally referred to as ‘device with lights and sounds’.

## 11 Conclusion and future perspectives

The present work describes the development process and testing of a feedback system, composed of a combination of visual and acoustic signals, integrated in the physical device (A)MICO designed to improve and facilitate the user experience while interacting with collaborative robots in production lines. The co-design process and the testing phase were conducted by involving users with ASD, which are potential end-users of the system.

The results confirm the importance of having further information to clarify those already provided by the cobot and are application-specific. Indeed, the information transmitted by current cobots usually refers to their state of activity, as described in Sect. 2.2. This further highlights the importance of developing a feedback system that gives specific information about the task.

Having more information about the cobot activity allows the operator to become more aware of the situation and achieve a higher level of autonomy. Starting form this, workplace can be redesigned to be more inclusive and accessible for other end-users, opening new job opportunities.

With regard to the sensory experience derived by the combination of acoustic and visual feedback, the level of acceptance depends on the preferences of the individual user. Indeed, considering the enormous heterogeneity of needs, not only related to ASD, the possibility of customising signals is an important aspect to be integrated into the final feedback system in order to make the workplace of the existing cobot system more accessible to all.

With this in mind, the design and development of accessible interfaces to achieve this purpose will certainly be the topic addressed in future related studies.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s12193-024-00444-x.

**Acknowledgements** The authors want to thank Auticon s.r.l. and AutAcademy for helping in the recruitment of participants. A special thanks to Simona Ravera for her precious support during the testing phase.

**Author contributions** All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Carla Dei and Matteo Meregalli Falerni. The integration of the electronic modules into the physical prototype and the connection to the general system were implemented by Matteo Meregalli Falerni.

Carla Dei wrote the first draft of the manuscript and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**Funding** This work was funded by the European Union's Horizon 2020 research and innovation programme, under grant agreement No 847926 (Mindbot: Mental Health promotion of cobot Workers in Industry 4.0). This study was also supported by the Italian Ministry of Health (Ricerca Corrente 2023–24 to Dr. E. Biffi).

**Data and code availability** All data supporting the present work are presented in the main manuscript and in the supplementary information.

## Declarations

**Conflict of interest** The authors declare no conflict of interest.

**Ethics approval and Consent to participate** The present study was conducted according to the guidelines of the Declaration of Helsinki and approval by the Ethics Committee of Istituto di Ricovero e Cura a Carattere Scientifico Eugenio Medea (protocol code N. 19/20CE of 20 April 2020) was obtained. All participants received an information sheet about the aims and procedures of the study. Before starting the data collection, they were asked to sign an informed consent, including consent to the processing of personal data.

## References

1. Peshkin M, Colgate JE (1999) Cobots. Ind Robot 26(5):335–341. https://doi.org/10.1108/01439919910283722
2. Weiss A, Wortmeier AK, Kubicek B (2021) Cobots in industry 4.0: a roadmap for future practice studies on human-robot collaboration. IEEE Trans Human-Machine Syst 51(4):335–345. https://doi.org/10.1109/THMS.2021.3092684
3. Taesi C, Aggogeri F, Pellegrini N (2023) COBOT applications—recent advances and challenges. Robotics 12(3):79. https://doi.org/10.3390/robotics12030079
4. Romero D, Bernus P, Noran O, Stahre J and Fast-Berglund Å. (2016) The Operator 4.0: Human Cyber-Physical Systems & Adaptive Automation towards Human-Automation Symbiosis Work Systems. IFIP Adv Inf Commun Technol. https://doi.org/10.1007/978-3-319-51133-7
5. Ávila-Gutiérrez MJ, Aguayo-González F, Lama-Ruiz JR (2021) Framework for the development of affective and smart manufacturing systems using sensorised surrogate models. Sensors 21(7):22–74. https://doi.org/10.3390/s21072274
6. Nomura T, Suzuki T, Kanda T and Kato K (2006) Measurement of anxiety toward robots. Proc - IEEE Int Work Robot Hum Interact Commun:372–377. https://doi.org/10.1109/ROMAN.2006.314462
7. Sciutti A, Mara M, Tagliasco V, Sandini G (2018) Humanizing human-robot interaction. IEEE Technol Soc Mag 37(1):22–29. https://doi.org/10.1109/MTS.2018.2795095
8. Varriale L, Briganti P, Volpe T, Minucci G (2023) Digital technologies for promoting the inclusion of workers with disabilities: a brief investigation. ITM Web Conf 51:03001. https://doi.org/10.1051/itmconf/20235103001
9. Johnston L, Beard LA and Bowden Carpenter L (2007) Assistive technology: access for all students. Pearson/Merrill Prentice Hall, Virginia
10. Mark BG, Hofmayer S, Rauch E, Matt DT (2019) Inclusion of workers with disabilities in production 4.0: legal foundations in Europe and potentials through worker assistance systems. Sustain 11(21):5978. https://doi.org/10.3390/su11215978
11. Christiernin LG (2017) How to describe interaction with a collaborative robot. ACM/IEEE Int Conf Human-Robot Interact: 93–94. https://doi.org/10.1145/3029798.3038325
12. Stohr M, Schneider M and Henkel C (2018) Adaptive Work Instructions for People with Disabilities in the Context of Human Robot Collaboration. Proc - IEEE 16th Int Conf Ind Informatics, INDIN 2018:301–308. https://doi.org/10.1109/INDIN.2018.8472070
13. Unger DD (2002) Employers' attitudes toward persons with disabilities in the workforce: myths or realities? Focus Autism Other Dev Disabl 17(1):2–10. https://doi.org/10.1177/108835760201700101
14. Johnson KR, Ennis-Cole D, Bonhamgregory M (2020) Workplace success strategies for employees with autism spectrum disorder: a new frontier for human resource development. Hum Resour Dev Rev 19(2):122–151. https://doi.org/10.1177/1534484320905910
15. Nicholas D, Mitchell W, Zulla R, Dudley C (2019) Perspectives of employers about hiring individuals with autism spectrum disorder: evaluating a cohort of employers engaged in a job-readiness initiative. J Vocat Rehabil 50:353–364. https://doi.org/10.3233/JVR-191018
16. European Institute for Design and Disability (EIDD) Stockholm Declaration© (2004). Available online: https://dfaeurope.eu/what-is-dfa/dfa-documents/the-eidd-stockholm-declaration-2004/
17. Froyen H (2012) Universal Design, A Methodological Approach. IHCD, Dutch
18. Burden AG, Caldwell GA, Guertler MR (2022) Towards human–robot collaboration in construction: current cobot trends and forecasts. Constr Robot 6:209–220. https://doi.org/10.1007/s41693-022-00085-0
19. Rodríguez-Guerra D, Sorrosal G, Cabanes I, Calleja C (2021) Human-robot interaction review: challenges and solutions for modern industrial environments. IEEE Access 9:108557–108578. https://doi.org/10.1109/ACCESS.2021.3099287
20. Brambilla C, Marani R, Romeo L, Lavit Nicora M, Storm FA, Reni G, Malosio M, D'Orazi T, Scano A (2023) Azure Kinect performance evaluation for human motion and upper limb biomechanical analysis. Heliyon 9(11):e21606. https://doi.org/10.1016/j.heliyon.2023.e21606
21. Scholz C, Cao H-L, El Makrini I, Niehaus S, Kaufmann M, Cheyns D, Roshandel N, Burkiewicz A, Shhaitly M, Imrith E, Rottenberg X, Gerets P (2024) Improving robot-to-human communication using flexible display technology as a robotic-skin-interface: a co-design study. Int J Intell Robot Appl. https://doi.org/10.1007/s41315-024-00343-0
22. Saren S, Mukhopadhyay A, Ghose D, Biswas P (2024) Comparing alternative modalities in the context of multimodal human–robot interaction. J Multimodal User Interfaces 18:69–85. https://doi.org/10.1007/s12193-023-00421-w

23. Mukherjee D, Hong J, Vats H, Bae S, Najjaran H (2024) Personalization of industrial human–robot communication through domain adaptation based on user feedback. User Model User-Adap Inter 34:1327–1367. https://doi.org/10.1007/s11257-024-09394-1
24. Su H, Qi W, Chen J, Yang C, Sandoval J, Laribi MA (2023) Recent advancements in multimodal human–robot interaction. Front Neurorobot 17:1084000. https://doi.org/10.3389/fnbot.2023.1084000
25. Gross S, Krenn B (2023) A communicative perspective on human-robot collaboration in industry: mapping communicative modes on collaborative scenarios. Int J Soc Robot. https://doi.org/10.1007/s12369-023-00991-5
26. Mpofu E, Tansey T, Mpofu N, Tu WM, Li Q (2019) Employment Practices with People with Autism Spectrum Disorder in the Digital Age. In: Potgieter I, Ferreira N, Coetzee M (eds) Theory, Research and Dynamics of Career Wellbeing. Springer, Cham. https://doi.org/10.1007/978-3-030-28180-9_15
27. Gentry T, Wallace J, Kvarfordt C, Lynch KB (2010) Personal digital assistants as cognitive aids for high school students with autism: results of a community-based trial. J Vocat Rehabil 32(2):101–107. https://doi.org/10.3233/JVR-2010-0499
28. Castro A, Silva F, Santos V (2021) Trends of human-robot collaboration in industry contexts: handover, learning, and metrics. Sensors 21(12):1–28. https://doi.org/10.3390/s21124113
29. Gervasi R, Capponi M, Mastrogiacomo L, Franceschini F (2024) Does size matter? Exploring the effect of cobot size on user experience in human–robot collaboration. Int J Adv Manuf Technol 133:5777–5791. https://doi.org/10.1007/s00170-024-14060-2
30. Bergman M, De Joode E, De Geus M and Sturm J (2019) Human-cobot teams: Exploring design principles and behaviour models to facilitate the understanding of non-verbal communication from cobots. CHIRA 2019 - Proc 3rd Int Conf Comput Interact Res Appl: 191–198. https://doi.org/10.5220/0008363201910198
31. Phillips E, Ososky S, Grove J and Jenstch F (2011) From tools to teammates: toward the development of appropriate mental models for intelligent robots. In: Proceedings from the human factors and ergonomics society 55th annual meeting, pp 1491–1495 https://doi.org/10.1177/1071181311551310
32. Rouillard J, Vannobel JM (2023) Multimodal interaction for cobot using MQTT. Multimod Technol Interact 7(8):78. https://doi.org/10.3390/mti7080078
33. D'Attanasio S, Alabert T, Francis C, Studzinska A (2024) Exploring multimodal interactions with a robot assistant in an assembly task: a human-centered design approach. VISIGRAPP. https://doi.org/10.5220/0012570800003660
34. Wright JL, Lakhmani SG, Chen JYC (2022) Bidirectional communications in human-agent teaming: the effects of communication style and feedback. Int J Human-Comput Interact 38:18–20. https://doi.org/10.1080/10447318.2022.2068744
35. Heinz M and Röcker C (2018) Feedback presentation for workers in industrial environments – Challenges and opportunities. Lect Notes Comput Sci (including Subser Lect Notes Artif Intell Lect Notes Bioinformatics) 11015 LNCS:248–261. https://doi.org/10.1007/978-3-319-99740-7_17
36. American Psychiatric Association. Diagnostic and Statistical Manual of Mental Disorders, 5th ed.; American Psychiatric Association: Washington, DC, USA, 2013.
37. World Health Organization. Available online: http://www.who.int/en/news-room/fact-sheets/detail/autism-spectrum-disorders.
38. Lorenz T, Frischling C, Cuadros R, Heinitz K (2016) Autism and overcoming job barriers: comparing job-related barriers and possible solutions in and outside of autism-specific employment. PLoS ONE 11(1):1–19. https://doi.org/10.1371/journal.pone.0147040
39. Abich J, Barber DJ (2017) The impact of human-robot multimodal communication on mental workload, usability preference, and expectations of robot behavior. J Multimodal User Interfaces 11(2):211–225. https://doi.org/10.1007/s12193-016-0237-4
40. Bensch S, Sun J, Bandera Rubio JP, Romero-Garcés A and Hellström T (2023) Personalised multi-modal communication for HRI, WARN workshop at the 32nd IEEE international conference on robot and human interactive communication, RO-MAN
41. Gwilt I, Rolph J, Eimontaite I, Cameron D, Aitken J, Mokaram S and Law J (2018) Cobotics: developing a visual language for human-robotic collaborations. In: Brunet, C., (ed.) Cumulus conference Paris 2018 – To get there: designing together, 11–14 Apr 2018, Paris, France. Cumulus , 106–127
42. Villani V, Fenech G, Fabbricatore M, Secchi C (2023) Wrist vibration feedback to improve operator awareness in collaborative robotics. J Intell Robot Syst 109:45. https://doi.org/10.1007/s10846-023-01974-4
43. Hoecherl J, Schmargendorf M, Wrede B and Schlegl T (2018) User-centered design of multimodal robot feedback for cobots of human-robotworking cells in industrial production contexts ISR 2018; 50th international symposium on robotics, Munich, Germany, 1–8. ISBN 9781510870314
44. Baraka K, Rosenthal S and Veloso M (2016) Enhancing human understanding of a mobile robot's state and actions using expressive lights. 25th IEEE Int Symp Robot Hum Interact Commun RO-MAN 2016:652–657. https://doi.org/10.1109/ROMAN.2016.7745187
45. Fernandez R, John N, Kirmani S, Hart J, Sinapov J and Stone P (2018) Passive demonstrations of light-based robot signals for improved human interpretability 2018. In: 27th IEEE international symposium on robot and human interactive communication (RO-MAN), Nanjing, China, 234–239, https://doi.org/10.1109/ROMAN.2018.8525728
46. Song S and Yamda S (2018) Effect of expressive lights on human perception and interpretation of functional robot. Conf Hum Factors Comput Syst - Proc 2018-April:1–6. https://doi.org/10.1145/3170427.3188547
47. Cha E, Fitter NT, Kim Y, Fong T, Matarić M (2018) Generating expressive light signals for appearance-constrained robots. Springer Proc Adv Robot 11:595–607. https://doi.org/10.1007/978-3-030-33950-0_51
48. Cao H, Scholz C, De Winter J, El Makrini I, Vanderborght B (2023) Investigating the role of multi-modal social cues in human-robot collaboration in industrial settings. Int J of Soc Robot 15:1169. https://doi.org/10.1007/s12369-023-01018-9
49. Tang G, Webb P, Thrower J (2019) The development and evaluation of Robot Light Skin: a novel robot signalling system to improve communication in industrial human–robot collaboration. Robot Comput Integr Manuf 56:85–94. https://doi.org/10.1016/j.rcim.2018.08.005
50. Storm FA, Chiappini M, Dei C, Piazza C, André E, Reißner N, Brdar I, Delle Fave A, Gebhard P, Malosio M, Pena Fernández A, Štefok S, Reni G (2022) Physical and mental well-being of cobot workers: a scoping review using the software-hardware-environment-liveware-liveware organization model. Human Factors Ergonom Manuf Serv Ind 32:419–435. https://doi.org/10.1002/hfm
51. Baraka K, Veloso MM (2018) Mobile service robot state revealing through expressive lights: formalism, design, and evaluation. Int J Soc Robot 10(1):65–92. https://doi.org/10.1007/s12369-017-0431-x
52. Bolano G, Roennau A and Dillmann R (2018) Transparent Robot Behavior by Adding Intuitive Visual and Acoustic Feedback to Motion Replanning. RO-MAN 2018 - 27th IEEE Int Symp Robot Hum Interact Commun 1075–1080. https://doi.org/10.1109/ROMAN.2018.8525671
53. Cha E, Matarić M and Fong T (2016) Nonverbal signaling for non-humanoid robots during human-robot collaboration. ACM/IEEE Int Conf Human-Robot Interact 2016-April:601–602. https://doi.org/10.1109/HRI.2016.7451876

54. ISO 11428:1996 Ergonomics - Visual danger signals - General requirements, design and testing. Available online: https://www.iso.org/obp/ui/en/#iso:std:iso:11428:ed-1:v1:en
55. ISO 11429:1996 Ergonomics - System of auditory and visual danger and information signals. Available online: https://www.iso.org/obp/ui/en/#iso:std:iso:11429:ed-1:v1:en
56. ISO 7731:2003 Ergonomics - Danger signals for public and work areas — Auditory danger signals. Available online: https://www.iso.org/obp/ui/en/#iso:std:33590:en
57. Barattini P, Morand C and Robertson NM (2012) A proposed gesture set for the control of industrial collaborative robots. Proc - IEEE Int Work Robot Hum Interact Commun: 132–137. https://doi.org/10.1109/ROMAN.2012.6343743
58. Quigley M, Gerkey B, Conley K, Faust J, Foote T, Leibs J, Berger E, Wheeler R and Y NG A (2015) ROS: an open-source Robot Operating System. IECON 2015 - 41st Annu Conf IEEE Ind Electron Soc:4754–4759. https://doi.org/10.1109/IECON.2015.73928437
59. Dei C, Meregalli Falerni M, Lavit Nicora M, Chiappini M, Storm FA and Malosio M (2023) Design of a multimodal device to improve well-being of autistic workers interacting with collaborative robots. Innov Prod Dev Manag, https://doi.org/10.48550/arXiv.2304.14191
60. Scheerer NE, Curcin K, Stojanoski B, Anagnostou E, Nicolson R, Kelley E, Georgiades S, Liu X, Stevenson RA (2021) Exploring sensory phenotypes in autism spectrum disorder. Mol Autism 12(1):67. https://doi.org/10.1186/s13229-021-00471-5
61. Yaguchi A, Hidaka S (2020) Unique relationships between autistic traits and visual, auditory, and tactile sensory thresholds in typically developing adults. Perception 49(4):405–421. https://doi.org/10.1177/0301006620907827
62. Persson H, Åhman H, Yngling AA, Gulliksen J (2015) Universal design, inclusive design, accessible design, design for all: different concepts—one goal? On the concept of accessibility—historical, methodological and philosophical aspects. Univ Access Inf Soc 14:505–526. https://doi.org/10.1007/s10209-014-0358-z
63. Steen M, Manschot M, de Koning N (2011) Benefits of co-design in service design projects. Int J Des 5(2):53–60. https://doi.org/10.1162/DESI_a_00207
64. Francis P, Balbo S, Firth L (2009) Towards co-design with users who have autism spectrum disorders. Univers Access Inf Soc 8:123–135. https://doi.org/10.1007/s10209-008-0143-y
65. Mondellini M, Prajod P, Lavit Nicora M, Chiappini M, Micheletti E, Storm FA, Vertechy R, André E, Malosio M (2023) Behavioral patterns in robotic collaborative assembly: comparing neurotypical and autism spectrum disorder participants. Front Psychol 14:1245857. https://doi.org/10.3389/fpsyg.2023.1245857
66. Brosnan M, Ashwin C, Lewton M (2017) Brief report: intuitive and reflective reasoning in autism spectrum disorder. J Autism Dev Disord 47:2595–2601. https://doi.org/10.1007/s10803-017-3131-3
67. Marco EJ, Hinkley LBN, Hill SS, Nagarajan SS (2015) Sensory processing in autism: a review of neurophysiologic findings. Pediatr Res 69(5):48–54. https://doi.org/10.1203/PDR.0b013e3182130c54.Sensory
68. Sadia T (2020) Exploring the design preferences of neurodivergent populations for quiet spaces. https://doi.org/10.31224/osf.io/fkaqj
69. Weber C, Krieger B, Häne E et al (2022) Physical workplace adjustments to support neurodivergent workers: a systematic review. Appl Psychol. https://doi.org/10.1111/apps.12431
70. Kuschner ES, Bennetto L, Yost K (2007) Patterns of nonverbal cognitive functioning in young children with autism spectrum disorders. J Autism Dev Disord 37(5):795–807. https://doi.org/10.1007/s10803-006-0209-8
71. Lord C, Cook EH, Leventhal BL, Amaral DG (2000) Autism spectrum disorders. Neuron 28(2):355–363. https://doi.org/10.1016/s0896-6273(00)00115-x
72. Kodak T, Bergmann S (2020) Autism spectrum disorder: characteristics, associated behaviors, and early intervention. Pediatr Clin North Am 67(3):525–535. https://doi.org/10.1016/j.pcl.2020.02.007
73. South M, Rodgers J (2017) Sensory, emotional and cognitive contributions to anxiety in autism spectrum disorders. Front Hum Neurosci 11:1–7. https://doi.org/10.3389/fnhum.2017.00020