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Language-free graphical signage improves human performance and reduces anxiety when working collaboratively with robots

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Abstract

As robots become more ubiquitous, and their capabilities extend, novice users will require intuitive instructional information related to their use. This is particularly important in the manufacturing sector, which is set to be transformed under Industry 4.0 by the deployment of collaborative robots in support of traditionally low-skilled, manual roles. In the first study of its kind, this paper reports how static graphical signage can improve performance and reduce anxiety in participants physically collaborating with a semi-autonomous robot. Three groups of 30 participants collaborated with a robot to perform a manufacturing-type process using graphical information that was relevant to the task, irrelevant, or absent. The results reveal that the group exposed to relevant signage was significantly more accurate in undertaking the task. Furthermore, their anxiety towards robots significantly decreased as a function of increasing accuracy. Finally, participants exposed to graphical signage showed positive emotional valence in response to successful trials. At a time when workers are concerned about the threat posed by robots to jobs, and with advances in technology requiring upskilling of the workforce, it is important to provide intuitive and supportive information to users. Whilst increasingly sophisticated technical solutions are being sought to improve communication and confidence in human-robot co-working, our findings demonstrate how simple signage can still be used as an effective tool to reduce user anxiety and increase task performance.

Keywords Human-robot interaction · Graphical signage · Anxiety towards robots · Flexible manufacturing · Collaborative robotics · Industry 4.0 · Technology acceptance

1 Introduction

The march of technology is leading us into the 4th industrial revolution (Industry 4.0), where highly connected, intelligent systems will enable processes that are more efficient, productive, and responsive to customer needs and demands [11, 37, 40]. Robotics, particularly in the manufacturing domain, will increasingly replace physically demanding and strenuous manual processes, and those that

require high precision and repeatability. In response, the role of the human workforce will adapt to make more use of our uniquely human attributes, such as our perceptual and cognitive abilities. For the foreseeable future, human abilities in these areas will continue to surpass those of robots, and effective industrial processes will continue to be reliant on a combination of the two.

Collaborative robotics, or human-robot co-working, is merging these traditionally segregated autonomous and manual modes of operation. New collaborative robots (cobots) allow processes and tasks to be shared between humans and robots, and support safe physical collaboration in shared workspaces. In addition to combining the benefits of automation (speed, accuracy, repeatability, load-bearing capacity) and manual labour (perception, cognition, manual dexterity, flexibility), this technology will give rise to entirely new process possibilities. However, advances in technology must be matched by support and training for users, for whom this will be a revolutionary way of working; without this support, and in the face of current anxieties around robots taking jobs, trust and

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acceptance of the technology will be low. In response, we are exploring engagement with users and utilisation of intuitive communication interfaces, as a means of supporting collaborative working with robots.

Social robotics research routinely demonstrates that experience of human-robot interaction (HRI) can shape an individual's view and their affective response towards robots [6, 7]. For example, people with experience of robots have significantly more positive attitudes towards them than people without [4]. Similar findings have been shown in field studies where retirement home residents who interacted with a mobile robot showed decreased negative attitudes towards robots [41]. Positive outcomes have also been reflected in the cognitive abilities of patients with dementia who have interacted with the Paro robot [50], while interactions with the AIBO robot dog are associated with decreased loneliness [3]. Furthermore, in education, robots have been shown to engage and motivate students, with the result of positively affecting their learning [1, 17]. In sum, interaction with robots in social and educational settings promotes positive attitudes toward robots, and can positively impact on mental well-being.

In manufacturing, the introduction of robots is likely to have a different impact on users. The types of robots, and the situations in which they are applied, are far removed from social and educational settings. Moreover, existing work in HRI for collaborative robotics tends to focus on users already experienced with high-tech automation and robotic systems [51]. Therefore, a key gap exists in understanding how unskilled workers with little experience with robots will be affected by the introduction of robots, and how to facilitate their transition from manual to semi-automated work processes.

To adopt new technology, an individual must be made to feel confident in their abilities with it [25, 44]. Graphical signage supports this by providing information necessary to respond to a given situation, and has many advantages over other communication methods when designed unambiguously and according to ergonomic principles [8, 12]: firstly, it can display clear instructions for individuals with little or no prior experience [45] (for example, Ikea furniture assembly instructions [12]); secondly, graphical signage does not depend on spoken language, making it suitable for multicultural environments and beneficial for non-native speakers [5]; finally, information presented in a succinct way can help people who have learning impairments such as dyslexia, as their cognitive load decreases and they have to process less information compared to written instructions [20]. In short, the benefits of displaying information in a graphical form increase accessibility to a task, with potential benefits of improved performance and well-being [2, 21, 28, 42, 48].

Graphical signage has been shown to help people complete tasks faster and with more accuracy, such as navigating in unfamiliar environments [42, 48], and can reduce the number of accidents in manufacturing and on roads/highways [2, 21]. In addition, graphical signage is often designed to help people understand the requirements of unfamiliar situations, and having such information can lead to greater empowerment and a sense of control [9, 52]. In a healthcare context, well-designed booklets and information leaflets can not only make patients aware of facts and give advice, but also encourage discussion and prompt questions [28]. This leads to the feeling of being in control and able to make important decisions [47], which in turn could decrease experienced stress [22, 36, 38]. Moreover, stress and decision-making anxiety can influence mental and physical illnesses [30], and it is expected that reducing uncertainty through the use of graphical signage can help improve the mental and physical well-being for the individual. Finally, anxiety and negative attitudes towards new technology can affect the level of trust people have towards robot co-workers [18]. This is particularly important in manufacturing settings where an individual's cognitive load is often already high [43] and may not extend to monitoring of co-workers. We propose the introduction of signs that provide hands-free information access, and offer clear and succinct instructions, could reduce cognitive load, and positively affect not only performance on the task but also a worker's well-being.

Although past research shows that HRI experience can decrease a participant's negative attitude towards robots [41], this decrease in anxiety depends on both the robot's behavioural characteristics [35] and the individual's expectation of the experience and interaction; the latter can be communicated and prefigured by the use of graphical signage [31]. The aim of the current research is to examine the impact graphical signage can have on HRI in a manufacturing context, and with novice users.

In this paper, we explore the impact of graphical signage on users of collaborative robots by observing the behaviour of human participants co-working with a robot on a manufacturing-like task. In the remainder of the paper, we describe our methods and results, and demonstrate that graphical signage does indeed improve accuracy and positive emotion in users, and that it can also decrease user anxiety.

2 Materials and methods

In [10], we introduced an earlier protocol for assessing the impact of graphical signage on users of collaborative robots. We extend that protocol here by introducing finalized graphical signage and a comprehensive description of

the measures and procedure for human-robot interaction trials (described in sections 2.4 and 2.5 and provided in Appendix B). Taking into account recent developments in the field (described in Section 1), we have also formed the following hypotheses for testing:

Hypothesis 1 (H1) *Use of signs: Users provided with task-relevant signage will evaluate the presented graphical signs as more effective in supporting task performance than those users presented with the task-irrelevant signage.*

Hypothesis 2 (H2) *Use of signs: Users provided with task-relevant signage will have better recall of the signs post-experiment than those users presented with the task-irrelevant signage.*

Hypothesis 3 (H3) *Use of signs: Users provided with task-relevant signage will look at signage longer during the experiment than those users presented with the task-irrelevant signage.*

Hypothesis 4 (H4) *Task performance: Users provided with task-relevant signage will look at signage longer during the experiment than those users presented with the task-irrelevant signage.*

Hypothesis 5 (H5) *Affect: Users provided with task-relevant signage will report decreased anxiety when compared to those users presented with no signage or task-irrelevant signage.*

Hypothesis 6 (H6) *Affect: Users provided with task-relevant signage will report decreased negative attitudes towards robots post-experiment when compared to those users presented with no signage or task-irrelevant signage.*

Hypothesis 7 (H7) *Affect: Users provided with task-relevant signage will display more positive valence facial expressions throughout the experiment when compared to those users presented with no signage or task-irrelevant signage.*

2.1 Design

This study used a mixed design of two repeated measures within three independent groups. Repeated measures of attitudes and anxiety towards robots (see section 2.5) were taken pre- and post-HRI task. The three independent groups used were presence of task-relevant graphical signage (experimental), presence of task-irrelevant graphical signage (active control), and no signage present (baseline control). An active control group was used to account for impact the mere presence of

any signage (task-relevant or otherwise) may have on HRI.

2.2 Participants

Ninety volunteers from University of Sheffield students and staff participated in the study, 51 were male and 39 were female, M age = 30.12, SD = 11.17. Participants were evenly distributed across groups (30 per group, Table 3) and offered an opportunity to win one of five \$10 Amazon vouchers for their participation in the study. It was emphasized that the opportunity to win vouchers did not depend on task performance, only task participation. The study was approved by the University of Sheffield Psychology Department ethics committee.

2.3 KUKA iiwa robotic arm and API

The experimental setup was based around interaction with a KUKA LBR iiwa 7 R800 housed in the Sheffield Robotics laboratory. This robot is a lightweight industrial collaborative robotic arm with seven degrees of freedom (Fig. 1). Each of its joints is equipped with torque and position sensing. An application programming interface (API) has been produced [29] for the robot to provide an interface to common middleware applications such as the robot operating system (ROS) [39] and Yet Another Robot Platform (YARP) [27].

Other APIs exist for the KUKA iiwa, such as [19] and [49] that focus on the interaction between operators and the

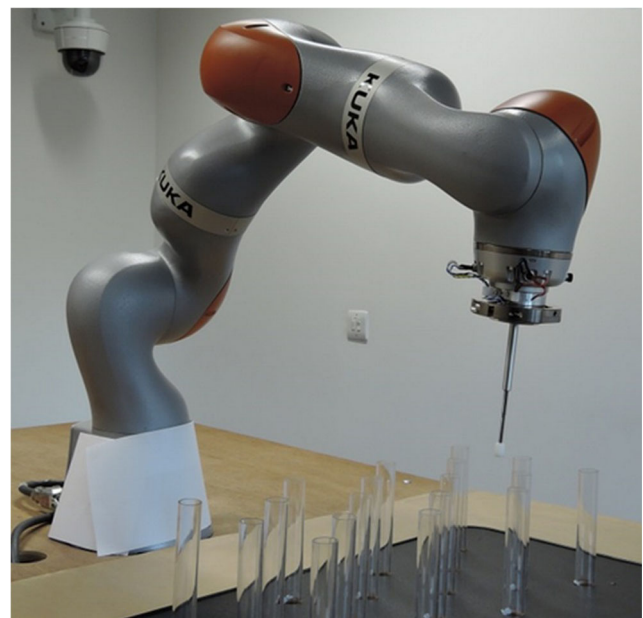


Fig. 1 The KUKA iiwa robotic arm with passive telescopic magnetic end-effector

robot. Khansari-Zadeh and Khatib [19] focus on learning actions from human demonstration, displaying different impedance to motions for critical parts of the exercise. Virga et al. [49] investigate force-compliant motion within the medical domain. Both of the APIs require specific components installing upon the KUKA iiwa, which require modification of the operational parameters on board the KUKA Sunrise controller; these either change the modes of operation or require custom installation of third-party libraries.

The API used within this paper [29] is a simple, stand-alone application. This can be placed directly on the KUKA Sunrise controller, and provides functionality without necessitating any modification of the control unit. It allows direct integration with ROS, without requiring any configuration. This enables full compatibility with the Robot Systems Toolbox in Matlab and Simulink, which widens the choice of development platforms for API users and allows the inclusion of model-based design as a choice for verifying potential applications [26].

This API was produced to support experiments and interface with other devices, without compromising the levels of safety natively provided. This has enabled the experiments described here, in which participants with no experience of robots are required to physically interact with a robot co-worker on a representative manufacturing task. For this study, the robot was set to be operated in a compliant safe mode ‘T1’, which placed limits on the speed of motion of the robot and required constant human monitoring (for full details about the robot control, see Appendix A).

2.4 Graphical language

A bespoke set of graphical symbols has been developed for this project, designed in accordance with ISO graphical signage conventions [14, 16]. Eight volunteers, unfamiliar with HRI, were presented with the graphical signage and were asked to identify (1) the meaning of each of the signs in their own words and (2) what changes would help the signs to become clearer. Further refinements and changes to add clarity were undertaken in response to this testing, resulting in the signage depicted in Fig. 2 that represents the following key HRI events:

- a The robot arm will move at a certain speed
- b The robot arm will move horizontally and vertically
- c In your interaction with the robot arm, there will be active and passive states
- d You can touch the robot
- e You will be within the robot’s area of operation
- f You should use a certain amount of force to move the robot arm

Due to the structure of the experiment, two sets of signage were developed—signage representing the necessary knowledge required to co-work with the robot (for example, speed and reach parameters of the robot) as seen in Fig. 2, and ‘active control’ signage which provided visually similar materials but did not provide task-relevant information for the co-worker in this context (for example, optimal temperature for the robot to operate) as seen in Fig. 3.

The project symbols will form the foundation for the development of a more extensive system of symbols that can be used to indicate a range of HRI scenarios.

2.5 Measures

The behavioural and self-report (questionnaires) measures are summarised in Tables 1 and 2. Complete versions of the questionnaires are presented in Appendix B.

All the questionnaires (self-report measures) in this study were presented via a computer using the online Qualtrics Insight Platform. Pre-experiment scores on all of *NARS S1* and *S2*, *RAS*, *RTI*, *participants programming skills*, *computer usage*, and *experience with robots* were used as a control for between-group differences. Measures with significant differences between groups are included as covariates in further analysis.

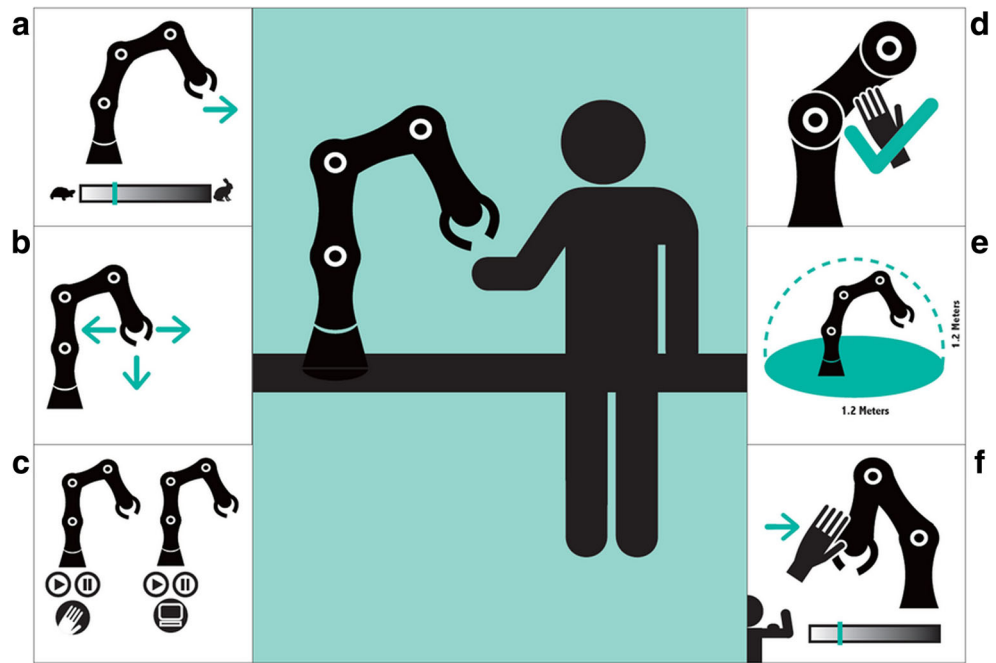
2.6 Procedure

After signing the consent form, each participant completed an online questionnaire before taking part in the HRI experiment. The questionnaire measured the participant’s *robot anxiety (RAS)*, *negative attitude towards robots (NARS S1 and S2)*, *computer usage*, *computer game and programming experience*, *safety risk taking attitude (RTI)*, and *experience with robots*.

Once in the lab, participants were instructed that they were going to be co-working with the KUKA iiwa robotic arm on an HRI task in a manufacturing-type scenario. The KUKA arm was stationed at a ‘workbench’, along with 18 narrow vertical tubes, six of which contained small bolts (Fig. 4). Participants were instructed that the bolts needed to be extracted from the tubes and placed in storage behind them. The bolts were inaccessible to the human (due to the depth and diameter of the tubes), and while the robotic arm could access each of the tubes, it needed human interaction to direct it to the tubes containing bolts.¹ As such, the task could be completed only by participants collaborating with the robotic arm. Participants were not provided with further instructions on *how* to operate the robot.

¹A video of the process is available online; https://youtu.be/_9PWZ2M68Xk

Fig. 2 Complete experimental condition sign with central co-bot activity symbol and information symbols to the left and right hand sides. **a** Speed. **b** Movement. **c** Stop and start. **d** Touch. **e** Reach. **f** Push (see main text for more information)



Experimental group participants were provided with graphical instructions indicating that the robot moves slowly, requires gentle force to be moved, and moves only within the specified area (Fig. 2). Robot safety systems would apply a hard stop to the robot should speed, force, or positional limits be exceeded, and the robot would not respond further until the lab assistant conducted a restart procedure. During the experiment, a collaborator observed the participants' performance behind closed curtains as a

safety measure in case the experiment needed to be aborted. The maximum time given to complete the task was 10 min.

Participants were informed that they were going to be filmed during the experiment, and the material collected would be used for data coding and further statistical analysis.

All three participant groups were given the same verbal instructions (as above), but only the experimental and the active control groups were presented with graphical signage

Fig. 3 Complete active control sign with central co-bot activity symbol and information symbols not directly relevant to the task performance. **a** Weight. **b** Sound. **c** Temperature. **d** Do not hit the robot with tools. **e** Work time. **f** Not water resistant

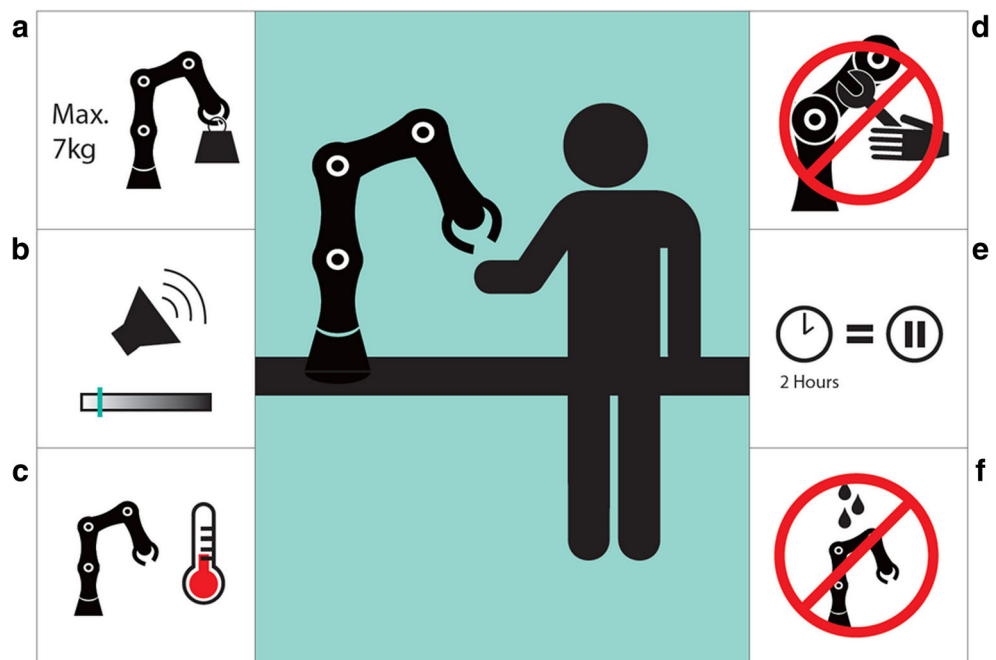
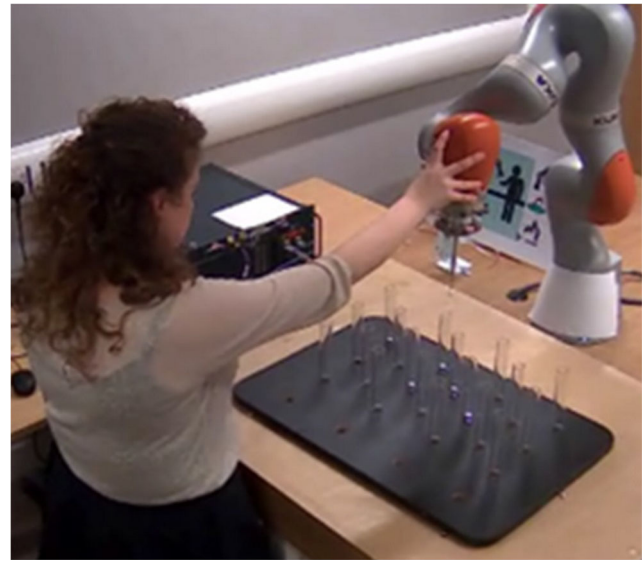


Table 1 Self-report measures used in this study

Measure	Authors	Details	Measurement method	Conducted
Negative Attitudes towards Robots Scale (NARS)	Nomura et al. [34]	Factors measuring negative attitudes towards interaction with robots (S1) and towards social influences of robots (S2)	Measured on scale from 1 (strongly disagree) to 5 (strongly agree)	Pre- and post-experiment
Robot Anxiety Scale (RAS)	Nomura et al. [33]	Factor measuring anxiety towards the behavioural characteristics of robots	A scale from 1 (I do not feel anxiety at all) to 6 (I feel very anxious)	Pre- and post-experiment
Risk Taking Index (RTI)	Nicholson et al. [32]	Participants' safety risk taking attitude (e.g. fast driving, city cycling without a helmet) now and in the past	A scale from 1 (never) to 5 (very often)	Pre-experiment
Experience with Robots	MacDorman et al. [24]	Questions assessed how often participants: attended robot-related events; read robot-related literature; watched robot-related media; had physical contact with a robot, or had built or programmed a robot; and what robots they have experience with	A 6-point scale (0, 1, 2, 3, 4, 5 or more times over a period specified in each question) with an open question for what robots they have experience with	Pre-experiment
Graphical Signage Effectiveness Questionnaire	Adapted from Galea et al. [13]	Three statements assess participants' perceived effectiveness of signs, and five statements assess effectiveness of the signage in assisting people to interact with the robotic arm	A scale from 1 (strongly agree) to 5 (strongly disagree), with an additional option of "I did not see any graphical signs"	Post-experiment
Sign recollection question	Custom measure	Participants were provided with all signage available in the experiment and had to indicate which signage they have seen (in case of baseline control, option "I have not seen any signage" was included)	False alarms (incorrect choices) and hit rate (correct choices) were calculated to acquire d' measure	Post-experiment
Technology usage and programming experience questions	Custom measure	How many hours per week participants used a computer for assignments/work, for browsing/socializing, and for playing computer games; participant programming experience	Participants indicated how many hours a week they performed on each activity and self-reported their programming experience on a 5-point scale from 1 (very inexperienced) to 5 (very experienced)	Pre-experiment

Table 2 Behavioural measures used in this study

Measure	Details	Measurement method
Accuracy	Participants ability to complete the task without error	Number of successfully completed trials / overall attempted trials
Response time	Response time was recorded for successfully completed trials	Measured in seconds from start to end of hand-guided robot interaction
Facial expressions	Coded automatically with Noldus FaceReader version 5 [23]. Three video cameras located in front of participant were used to record participants facial expressions (neutral, happy, sad, angry surprised, scared and disgusted) and the valence (happy - (sad + angry + scared + disgusted) during successfully completed and failed trials)	Measures emotion intensity and duration
Gaze duration	Gaze duration was automatically acquired by Noldus FaceReader version 5 software from a video recorder placed below the signage.	Measured in number of frames

**Fig. 4** Experimental task set up. Six bolts distributed across 18 long narrow tubes, with signage (experimental condition) visible by the robot

(Figs. 2 and 3 respectively), which was located on the table on the left side of the robot (105 cm from the table edge where participants were standing, just behind the webcam used to record facial expressions). Additional signage was placed outside the room on the lab door, indicating that inside, either humans are working with robots (for the experimental group) or humans are working with industrial tools (for the active control group).

Immediately following the HRI task, participants completed the *Graphical Signage Effectiveness Questionnaire* (see Appendix B). Their *Robot Anxiety (RAS)* and *Negative Attitudes towards Robots (NARS)* were measured once again. Finally, participants were fully debriefed about the aims of the experiment. The whole experiment lasted approximately 20 min.

3 Results

3.1 Group differences

A one-way ANOVA was performed to examine pre-trial distribution of participants across the three groups for the following demographic and psychological measures: age, computer usage for work and leisure (hours per week), computer gaming and *NARS (S1, S2)*, *RAS*, *RTI*, programming experience, and experience with robots. There was a significant difference in the *NARS S1*, $F(2, 89) = 3.70$, $p = .029$, $\eta_p^2 = .077$. The experimental group had significantly lower *NARS S1* scores compared to the active control group ($p = .029$, Bonferroni corrected), yet not

Table 3 Control variable mean values (and SD) for experimental, active control, and control groups

	Group		
	Experimental	Active control	Control
Male/female	17/13	16/14	18/12
Age	29.37 (7.95)	31.67 (12.89)	29.33 (12.26)
NARS			
S1	10.83 (3.00)	13.53 (4.49)	11.63 (4.21)
S2	13.33 (2.32)	13.60 (2.91)	13.37 (3.39)
RAS behavioural	10.53 (4.09)	11.53 (4.07)	10.87 (5.01)
Experience with robots	17.03 (8.33)	13.80 (8.19)	15.83 (8.53)
Computer use			
Work (h/week)	28.82 (14.81)	24.30 (16.67)	23.93 (14.12)
Leisure (h/week)	14.18 (16.54)	11.95 (10.82)	11.68 (10.68)
Gaming (h/week)	2.32 (4.11)	1.58 (2.51)	4.20 (7.74)
Programming experience	2.60 (1.30)	2.23 (1.22)	2.70 (1.15)
Safety RTI			
Present	1.93 (1.01)	2.13 (1.17)	2.10 (1.18)
Past	2.33 (1.15)	2.13 (1.04)	2.57 (1.38)

significant compared to the control group ($p = .198$). The difference between the active control and control groups was not significant ($p > .999$; Table 3). There were no further significant differences between groups for any of the remaining pre-test measures ($F(2, 89) \leq 1.97$, $p \geq .145$, $\eta_p^2 \leq .04$). All further ANOVAs are conducted with NARS S1 as a covariate, unless otherwise specified.

3.2 Effectiveness of graphical signs

3.2.1 Gaze

The ANOVA on gaze duration (measured in number of frames) reveals a significant difference between participant groups for duration of gaze towards the graphical signage (or, for the control group, gaze direction towards the site vacant of signage), $F(2, 86) = 8.35$, $p < .001$, $\eta_p^2 = .163$ (Table 4). Post hoc analysis with Bonferroni adjustment for multiple comparisons revealed that those in the experimental group looked at the graphical signage for longer (number of frames looking at signage/overall number of frames) compared to both the active control ($p = .045$) and control groups ($p < .001$), yet there was no significant difference between active control and control groups ($p = .447$).

3.2.2 Sign recollection

The ANOVA on a d' sensitivity analysis for recollection of the graphical signage presents a significant difference between groups for recall of signs, $F(1, 57) = 5.24$, $p = .026$, $\eta_p^2 = .082$ (Table 4). The experimental group had a significantly better recollection of signs than the active control group. To investigate the possibility that better performance during the HRI task is associated with better sign recollection after the task, Pearson's correlation analysis was performed on the experimental group. The results showed that there was no significant relationship between accuracy and d' ($r = -.25$, $p = .176$), suggesting that the experimental group's better recall of the signage was not associated with their accuracy on the task.

3.2.3 Graphical signage effectiveness questionnaire

The questionnaire consisting of eight questions measuring participants' evaluation of graphical signage effectiveness was reliable (Cronbach's alpha = 0.86). Answers from the experimental and active control group on each question were compared using a Mann-Whitney non-parametric test for two independent samples. Control group participants

Table 4 Summary of statistically significant comparisons in graphical signage effectiveness measures, graphical signage effects on performance, and emotional effects of graphical signage

Measure (Independent → Dependent variable) ^a	Covariate	Main effect of independent variable	Mean (SD) of dependent variable		
			Experimental	Active control	Control
Group → Gaze duration towards signs		$F(2, 86) = 8.35, p < .001, \eta_p^2 = .16^b$	0.13(0.10)	0.05(0.08)	0.08(0.05)
Group → signs recollection (d')		$F(1, 57) = 5.24, p = .026, \eta_p^2 = .082^b$	2.08(0.53)	1.57(0.96)	N/A
Group → Accuracy rate	NARS SI	$F(2, 86) = 4.80, p = .011, \eta_p^2 = .100^c$	0.65(0.26)	0.49(0.22)	0.49(0.27)
Group → Valence over accuracy	NARS SI; age	$F(2, 82) = 3.55, p = .033, \eta_p^2 = .100^c$	1.79(2.61)	2.58(2.64)	-6.25(2.59)
Accuracy → RAS change between pre- and post-experiment	NARS SI	$F(4, 85) = 2.14, p = .083, R^2 = .073^{d,e}$	-0.13(3.15)	0.97(3.82)	0.43(3.74)

^aThe effects of independent variable on dependent variables (for example: effect of participant group on gaze duration towards signage)

^bOne-way ANOVA

^cANCOVA

^dModerated regression (moderator-participant group)

^eAccuracy by Group interaction: $F(1, 85) = 4.43, p = .038, R^2 = .12$

were not included in this analysis as they were not presented with any graphical signage and in the questionnaire indicated that they did not see any signage.

The analysis of experimental and active control groups revealed a significant difference in response to the statement “The graphical sign reinforced my decision concerning how to operate the robotic arm” ($U = 279, n = 58, p = .022, r = .30$). The experimental group agreed with this statement while the active control group disagreed (Table 5). The differences between groups on other statements were not significant ($U \geq 318, n = 58, p \geq .102, r \leq .21$) except a trend difference for statements “I found graphical signs helpful” and “I found the signs of no use” ($U = 312, n = 58, p = .078, r = .23; U = 306, n = 58, p = .068, r = .24$; Table 5). More participants from the experimental group agreed that signs were helpful and disagreed on signs being of no use, while in the active control group, participants disagreed with the statement that signs were helpful and agreed that they were of no use.

Participants in the experimental and active control groups were affected by the signage differently. In comparison to those in the active control group, participants in the experimental group: looked towards the signage for longer, more accurately identified which signs they saw during the experiment, and indicated that signage reinforced their decision on how to operate the arm. Results suggest that the task-relevant signage is used by participants during the HRI scenario, and further analysis was conducted to investigate the impact of signage on task performance.

3.3 Graphical signage effects on performance

To investigate if graphical signage had an effect on participants’ task performance accuracy rate (collected bolts per number of trials) or response time for successful trials, two separate ANCOVA’s controlling for pre-trials *NARS SI* with an independent variable of group (experimental, active control, control) were constructed.

3.3.1 Accuracy rate

The analysis revealed a significant main effect of group ($F(2, 86) = 4.80, p = .011, \eta_p^2 = .100$; Table 4) and a significant influence of *NARS SI* covariate ($F(1, 86) = 2.12, p = .149, \eta_p^2 = .024$). Further investigation of the main effect of group with Bonferroni post hoc tests revealed that the experimental group had a higher accuracy than the active control ($p = .019$) or control ($p = .036$) groups. The difference in accuracy between control and active control groups was not significant ($p > .999$; Fig. 5).

Table 5 Percentage agreement for *Graphical Signage Effectiveness Questionnaire*^a statements

	Attitudes towards signage			Beliefs of signage's support towards HRI task performance				
	Confusing	Helpful ^b	No use ^b	Assisted operation	Reinforced decision ^c	No difference	Quick decision	Stop hesitate
Experimental								
Agree	70.00	50.00	26.67	50.00	50.00	26.67	26.67	63.33
Neither agree nor disagree	20.00	16.67	23.33	6.67	6.67	20.00	20.00	16.67
Disagree	10.00	33.33	50.00	43.33	43.33	53.33	53.33	20.00
Active control								
Agree	50.00	20.00	43.33	16.67	13.33	40.00	10.00	53.33
Neither agree nor disagree	16.67	13.33	23.33	26.67	16.67	16.67	20.00	13.33
Disagree	26.67	60.00	26.67	50.00	63.33	33.33	63.33	26.67

^aQuestionnaire responses “slightly agree” and “strongly agree” were combined into the “agree” category, similarly “strongly disagree” and “slightly disagree” were combined into the “disagree” category. The “Neither agree nor disagree” category was left unchanged. This was done only in this table for the ease of viewing results for experimental and active control groups

^b $p < .1$

^c $p < .022$

3.3.2 Response time

The comparison of the average response time between groups with ANCOVA revealed that response times did not significantly differ between groups ($F(2, 21.37) = 1.75$, $p = .198$, $\eta_p^2 = .141$).

The analysis shows that the experimental group participants collected more bolts in a lower number of trials compared to the control and active control groups. However, there was no significant difference between the active control and control groups. This result shows that graphical signage relevant to the task helps individuals to be more effective in completing it. The mean response time analysis

did not reveal any significant differences between groups. Further analysis of response time change depending on trial number was not possible due to a number of participants successfully completing less than six trials (Table 6).

3.4 Emotional effects of graphical signage

So far, the results show that the experimental graphical signage promotes increased accuracy. However, the questions about graphical signage effects on participants' anxiety (*RAS*) and negative attitudes towards robots (*NARS*) and their facial expressions (emotions) while interacting with robot are yet to be answered.

Fig. 5 Mean accuracy (collected bolts/number of trials) as a function of group (experimental, active control, control; +/- SE)

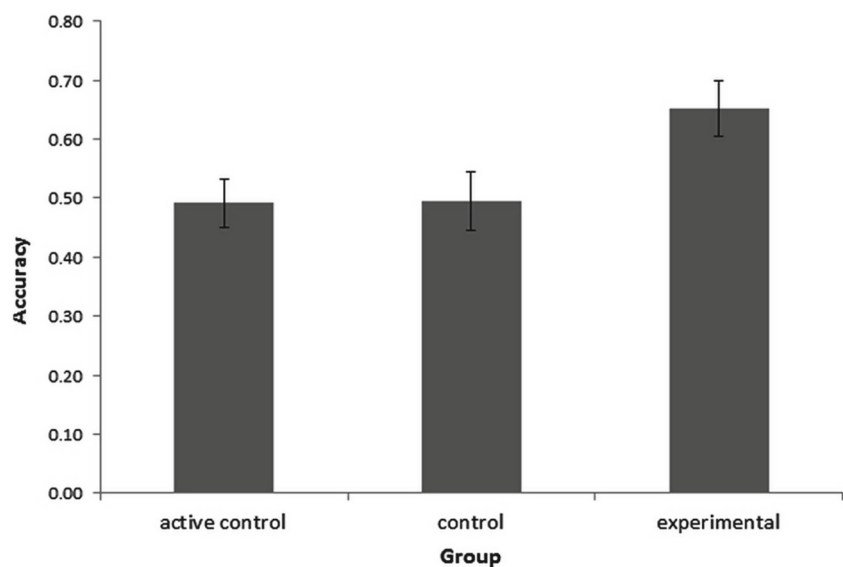


Table 6 Number of successfully completed trials for experimental, active control, and control groups

Group	Trials		
	0–2	3–4	5–6
Experimental	2	5	23
Active control	5	9	16
Control	4	7	18

3.4.1 Robot anxiety and negative attitudes towards robots

The investigation into whether the graphical signage had an effect on the change between pre- and post-trial RAS and NARS (*S1* and *S2*) scores with ANOVA showed no significant difference between groups ($F(2, 89) \leq .71$, $p \geq .496$).

Three separate moderated regressions for each dependent variable of change between post- and pre-trial RAS, NARS *S1*, and NARS *S2* were done using PROCESS syntax [15]. In these regression models, the independent variable was accuracy, moderator-participant group (experimental, active control, and control) and covariate was NARS *S1*.

The main effect of the RAS scores was at a trend significance ($F(4, 85) = 2.14$, $p = .083$, $R^2 = .073$; Table 4), but accuracy by group interaction was significant ($F(1, 85) = 4.43$, $p = .038$, $R^2 = .12$). The group effects of accuracy on the RAS scores change were significant only in the experimental group, ($b = -4.93$, $t = -2.85$, $p = .006$), but not in active control ($b = -1.74$, $t = -1.23$, $p = .223$) or control groups ($b = 1.44$, $t = .61$, $p = .545$; Fig. 6).

The analysis for NARS *S1* and NARS *S2* scores did not yield significant results ($F(4, 85) \leq 1.68$, $p \geq .162$).

The results suggest that higher accuracy predicts a greater decrease in the *Robot Anxiety Scale*, but it is moderated by group. Only the experimental group participants with higher accuracy show a significant decrease in the RAS scores (difference between post experiment-pre experiment scores).

3.4.2 Facial expressions

Facial expressions were coded with Noldus FaceReader version 5 software automatically to acquire measures of emotion intensity and duration of seven facial expressions (neutral, happy, sad, angry surprised, scared, and disgusted) and the valence (happy – (sad + angry + scared + disgusted)) [23].

To investigate group differences in intensity and duration of seven basic emotions, one-way between group ANOVA's with within-subject variables of emotion (neutral, happy, sad, angry, surprised, scared, and disgusted) and a between-subject variable of participant group (experimental, control,

and active control), and a covariate of NARS *S1* pre-experiment score were constructed. The analyses did not show significant differences in intensity of the seven facial expressions overall, successful and failed trials, or emotion duration ($F(2, 89) \leq 1.84$, $p \geq .165$).

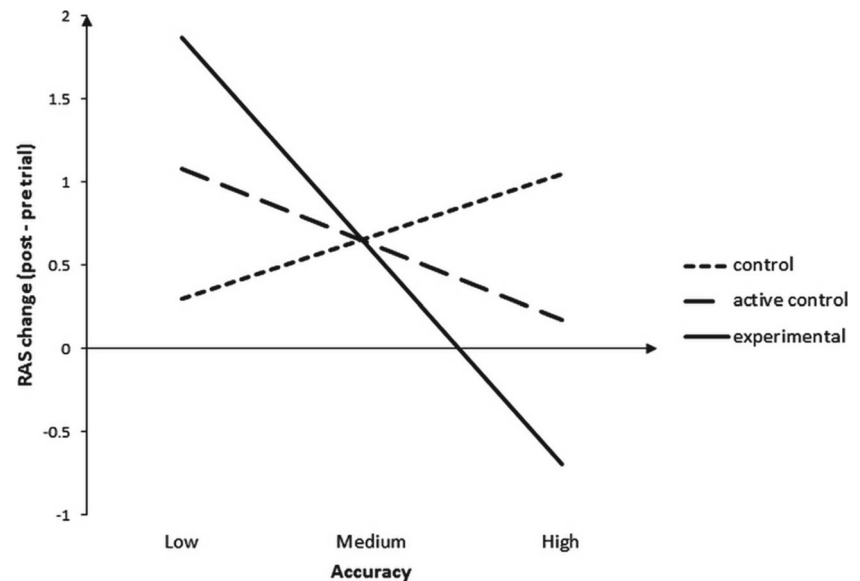
As there was a significant correlation between participants' age and emotional valence over the successful trials (Pearson's $r = -.256$, $p = .017$), and as it has been previously shown that older people have higher emotion control ability [46], an additional analysis was performed to compare the valence of the three participant groups in successful trials (from the point participants touched the robot, until the robot returned to the start position with a bolt), with a covariate of NARS *S1* and age. This analysis showed a significant main effect of group ($F(2, 82) = 3.55$, $p = .033$, $\eta_p^2 = .08$; Table 4) as well as covariate of age ($F(1, 82) = 7.12$, $p = .009$, $\eta_p^2 = .080$), but not NARS *S1* ($F(1, 82) = .34$, $p = .559$, $\eta_p^2 = .004$). A Bonferroni post hoc test showed that control group participants had valence at a trend level lower in comparison to active control ($p = .060$) and experimental groups ($p = .093$), yet experimental and active control groups did not differ ($p > .999$). This effect was observed only in valence over the successful trials, but not the failed trials.

The analysis showed that increased accuracy can be a predictor of the decrease in participants RAS scores after the experiment compared to pre-experiment levels, yet this effect was observed only in the experimental group. Furthermore, results from the facial expressions analysis showed that participants having signage (both relevant and irrelevant to the task) have positive emotional valence over successful trials while the 'no signage' participants' valence is negative. It is important to note that the differences were only at a trend level. There were no differences between the groups in failed trials.

4 Discussion

The current study explored the effect graphical signage has on participants' performance of a manufacturing-type HRI task. In addition, the *Negative Attitudes towards Robots Scale* (NARS), the *Robot Anxiety Scale* (RAS), and facial expressions and emotional valence of the participant during successful and failed trials were recorded. The main results show that participants in the experimental group had higher task completion accuracy than those in the active control and control groups. Furthermore, analysis of facial expression valence over successful trials revealed that both experimental and active control groups had a higher positive emotional valence compared to the control group. However, only in the experimental group did increased accuracy result in decreased anxiety towards robots after the experiment.

Fig. 6 The effect of accuracy on change in RAS score between post- and pre-experiment moderated by group (experimental, active control, and control) while controlling for the NARS S1 pre-experiment scores



These results cannot be explained by group differences as participants' age, *computer usage for work and leisure, gaming, NARS S2, RAS, RTI, programming experience, and experience with robots* did not significantly differ between groups. The only significant difference was observed in *NARS S1* scores, where the experimental group had significantly lower *NARS S1* scores compared to the active control group. As a result, *NARS S1* was entered as a covariate in further analysis.

Several control measures were taken to consider different effects of signage on the experimental and active control groups. First, the experimental group's gaze duration (frames ratio towards the signage) was significantly higher compared to both control groups, but active control and control group gaze duration to the location of signage did not differ significantly. Second, after the interaction with a robot, d' analysis showed that the experimental group recalled the signage more accurately than the active control group suggesting this group's participants were paying more attention to the signage. It is possible that better recollection of the signs reinforces performance, and vice versa—performance on the task reinforces recollection of the signs. However, correlation analysis did not reveal significant association between accuracy and d' in the experimental group. This indicates that the experimental group's better recall of the signs was not associated with their accuracy scores on the task.

Finally, the *Graphical Signage Effectiveness Questionnaire* revealed significant differences between experimental and active control groups regarding the statement that "The sign reinforced my decision concerning how to operate the robotic arm"; the majority of the experimental group participants agreed with the statement whilst the active control group mostly disagreed with this statement. Moreover,

a trend difference on the statements "I found graphical signs helpful" and "I found the signs of no use" showed that the experimental group found the signs more valuable for the task performance compared to the active control group. These results indicate that participants were affected by graphical signage differently; in comparison to the active control group, the experimental group looked longer at the signage, had a more accurate recollection of it, and indicated that signage reinforced their decisions of how to operate the robot.

The main finding of the study provides evidence that graphical signage improves accuracy: experimental group participants collected more bolts with less unnecessary trials, and they also triggered hard stops and directed the robot to empty tubes less often. This is consistent with previous studies showing that with more information about a particular task, an individual's accuracy increases; for example, it can result in quicker navigation of unfamiliar settings [42, 48] and decreased number of accidents in manufacturing and road safety situations [2, 21].

In the current study, graphical signage also affected the participants' anxiety towards robots measured with the *RAS*. The moderated regression showed that with increasing accuracy, post-trial scores on the behavioural subscale of the *RAS* were reduced compared to pre-trial scores on this scale, but only in the experimental group. A possible explanation lies in participants' sense of empowerment and knowledge of the processes they are going through. Graphical signage is designed to help people understand the requirements of unfamiliar situations, and this information can lead to greater empowerment and a sense of control [47] and decrease the levels of stress experienced [22, 36, 38]. Additionally, negative attitudes towards robots decrease after having interacted with robots [41]; however, the

decrease in anxiety depends on the robot's behavioural characteristics [35]. In the current study, there was no significant result in the change in negative attitudes (measured with the *NARS*) before and after the interaction with the robot in the three participant groups. On the other hand, *RAS* significantly decreased after interaction with the robot in the experimental group. As the signage provides information about the robot's characteristics, most likely it influenced participants' expectations of the robot's abilities and manoeuvrability [31].

Finally, the facial expression analysis revealed differences in facial expression valence on successful trials between the groups. As there was a significant negative correlation between participant age and their emotional valence, age was added as a covariate in this analysis. The comparison of valence between three groups showed higher valence during successful trials in the experimental and active control groups compared to the control group. Past research shows that individuals' emotion regulation improves with age [46], and the trend effect was observed in the current study by controlling for possible age influence on participants' emotion expression. Conversely, the failed trials analysis did not reveal any significant differences. It is likely that the mere appearance of signs is enough to trigger more positive feelings compared to the no signage group, where individuals do not know whether it is possible and safe to interact with robot directly. As the experimental task was not designed to trigger emotions, and in fact its repetitive nature could be used as a baseline for studies exploring emotional processes, further studies are needed to fully investigate differences in emotional valence between groups by exploring participants' emotion regulation and their facial expressions during manufacturing HRI tasks.

4.1 Limitations and future directions

There are several limitations to this study. Firstly, the responses on the *Graphical Signage Effectiveness Questionnaire* indicated that 70% of participants in the experimental group found signage to be confusing. Lack of clarity is a possible limitation of some of the current graphical stimuli, yet accuracy results across groups suggest that the experimental group still had a better performance compared to the control groups. As there was no significant group difference before the interaction with the robot (*NARS SI* was entered as a covariate in the analyses), this only indicates that performance may be further improved with additional development of the signage. To clarify which signs were least clear, we asked four additional participants their opinion of the experimental group signage during the task. The most confusing signs were the active and passive states of HRI (Fig. 2c) and the force necessary to move the robot

(Fig. 2f). The signs showing that an individual can touch the robot (Fig. 2d), and that it moves slowly (Fig. 2a) were indicated to be the most useful. Three out of four participants suggested that having written text or having signs in a particular order resembling the task process would be helpful while working with a robot.

Secondly, the participant population of the current experiment was drawn from university staff and students. Testing the same paradigm with participants from manufacturing industry would provide further insights in the effects graphical signage has on human-robot co-working. The improvements are being incorporated into our further work.

5 Conclusions

As collaborative robots are deployed in the workplace, care must be taken to ensure that workers are both accepting of this new technology and are appropriately trained and supported to provide confidence in its operation. Whilst substantial research is being directed towards the technical facets of safe human-robot collaboration, little has been done to address the human factors of trust and acceptance in the workforce. In this work, we have shown, for the first time, how simple instructional signage can improve participants' performance and confidence whilst undertaking a collaborative manufacturing-type task with a robot.

This study involved 90 participants across three groups: an experimental group was presented with graphical signage related to the task, an active control group was presented with irrelevant signage, and a control group was presented with no signage whatsoever. Participants in both the experimental and active control groups showed higher emotional valence, compared to the control group, indicating the mere appearance of signs was sufficient to positively impact on user feelings. However, only in the experimental group were participants significantly more productive, showing that improved robot usability can be attributed to relevant instructional signage. Furthermore, only in the experimental group did the anxiety of participants correspond to their success rate (with greater task success leading to lower anxiety), suggesting a positive feedback loop between signage and successful actions leads to increased confidence.

In this initial study, participants were recruited from an academic environment, and not from a more representative manufacturing workforce. To substantiate our findings, we are embedding our continuing work in manufacturing environments with participants drawn from the industrial workforce. Our initial results are validating those from this study: that instructional graphical signage produces positive emotions in users, improves productivity, and leads to reduced anxiety when reinforced by successful robot operation.

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Author contribution All authors contributed equally to this work.

Compliance with ethical standards The study was approved by the University of Sheffield Psychology Department ethics committee.

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Appendix A: robot control

The practical human-robot collaborative process used in this experiment was carried out using a KUKA LBR iiwa 7 R800 operating in both hand-guided and autonomous modes. For the purposes of safety, the robot was operated in ‘T1’ mode.² This resulted in a maximum Cartesian velocity at the end effector of 250mm/s.

The position of the robot in Cartesian space can be defined by the tuple, $Position = \{X, Y, Z, A, B, C\}$, where $\{X, Y, Z\}$ represents the displacement around the X, Y, and Z axes respectively, and $\{A, B, C\}$ represents the rotation about the X, Y and Z axes. A series of X-Y tube locations, $\{Tubes\}$, were set up on the table at a height of (Z_{lower}). An operating height (Z_{raised}) was defined that would allow the telescopic picking tool mounted on the robot to move above freely above the tubes in the X-Y plane with a clearance of around 1cm. A home position, ($Position_{home}$), was set between the operator and tube locations, at a height of (Z_{raised}).

In hand-guided mode, triggered by applying a 0.2-N force to the wrist of the robot, the operator was able to move the end effector in the X-Y plane but prevented from movement rotationally about each axis and in the Z-plane by restricting the robot’s compliance settings. The compliance settings for hand-guided ($Compliance_{Manual}$) and autonomous ($Compliance_{Auto}$) modes are shown in Table 7.

²A member of the research team enabled the robot’s safety switches whilst sat out of view from the participant behind a screen. The researcher monitored participants interacting with the robot via CCTV, and could stop the robot at any time

Control algorithm

The robot control algorithm comprises repeated loops of hand-guided operation followed by autonomous-mode operation. These begin with the robot in the home position, waiting for the operator to enable hand-guiding mode by applying the necessary $>0.2\text{-N}$ force.

Once in hand-guiding mode, the operator is free to move the end effector within the X-Y plane above the tube locations. Once the operator releases the robot (i.e. no X-Y forces are applied), the robot switches to autonomous mode and moves to the nearest tube. If the user applies a force, a 3-s timer is started. If an X-Y force is applied, the timer is reset so that the robot remains in hand-guided mode until the forces are removed again and the timer expires. If no X-Y forces are applied, the robot switches to autonomous mode.

Once in autonomous mode, the robot makes a refining move (in the X-Y plane) to the nearest known tube location. Once in position, the robot then makes two vertical movements: firstly to $Z = Z_{lower}$, which places the magnetic probe in contact with potential objects for picking, then back to $Z = Z_{raised}$, which retrieves picked objects from the tubes. Finally, the robot moves back to the home position for the operator to retrieve any picked objects, and waits for initiation of the next hand-guided sequence. All autonomous end effector motions are linear in X-Y or Z directions, with joint accelerations governed by the KUKA control software.

Pseudo-code for the process described above is given in Algorithm 1.

Algorithm 1 Algorithm for operation

```

1: Move to  $Position_{home}$ 
2: if  $EndEffectorForce > 0.2N$  then
3:   Set compliance to  $Compliance_{Manual}$ 
4:   while true do
5:     while  $EndEffectorForce > 0.2N$  do
6:        $SelectedTubeLocation = FindNearestTube$ 
7:       Set compliance to  $Compliance_{Auto}$ 
8:       Move to  $SelectedTubeLocation$  at height  $Z_{raised}$ 
9:       while  $EndEffectorForce > 0.2N$  do
10:        Start timer
11:        Set compliance to  $Compliance_{Manual}$ 
12:        while  $timer < 3s$  do
13:           $SelectedTubeLocation = FindNearestTube$ 
14:          if  $EndEffectorForce > 0.2N$  then
15:            Reset timer
16:            Set compliance to  $Compliance_{Auto}$ 
17:            Move to  $SelectedTubeLocation$  at height  $Z_{raised}$ 
18:            Wait 1 second
19:          Move to  $SelectedTubeLocation$  at height  $Z_{lowered}$ 
20:          Move to  $SelectedTubeLocation$  at height  $Z_{raised}$ 
21:        Move to  $Position_{home}$ 

```

Table 7 Robot parameters in hand-guided and autonomous modes

	Maximum cartesian velocity (mm/s)	X-Axis compliance (X_c) (N/m)	Y-Axis compliance (Y_c) (N/m)	Z-Axis compliance (Z_c) (N/m)	Rotational X-Axis (A_c) compliance (Nm/rad)	Rotational Y-Axis (B_c) compliance (Nm/rad)	Rotational Z-Axis (C_c) compliance (Nm/rad)
Hand-Guided mode (HGM)	250	10	10	5000	300	300	300
Autonomous mode (AM)	250	5000	5000	5000	300	300	300

Appendix B: questionnaires

Questionnaires used in the study:

Fig. 7 Signage recollection question. “Please indicate which signs you have seen during the experiment”, shown in Figure 7 (graphics also used in signage effectiveness questions)



Table 8 Negative attitudes towards robot scale [33]

		Strongly disagree	Slightly disagree	Feel exactly neutral	Slightly agree	Strongly agree
S1 - negative attitudes towards interaction with robots	I would feel uneasy if I was given a job where I had to use robots	1	2	3	4	5
	The word “robot” means nothing to me	1	2	3	4	5
	I would feel nervous operating a robot in front of other people	1	2	3	4	5
	I would hate the idea that robots or artificial intelligences were making judgements about things	1	2	3	4	5
	I would feel very nervous just standing in front of a robot	1	2	3	4	5
	I would feel paranoid talking with a robot	1	2	3	4	5
S2 - negative attitudes towards social influence of robots	I would feel uneasy if robots really had emotions	1	2	3	4	5
	Something bad might happen if robots developed into living beings	1	2	3	4	5
	I feel that if I depend on robots too much, something bad might happen	1	2	3	4	5
	I am concerned that robot would be a bad influence on children	1	2	3	4	5
	I feel that in the future, robots will be commonplace in society	1	2	3	4	5

Participants were asked: “Please indicate your reaction to each of the statements. You will probably find that you agree with some of the statements, and disagree with others, to varying extents. There are no right or wrong answers, just give your first impression without taking too much time”

Table 9 Robot anxiety scale [34] (subscale S2 - anxiety towards behavioural characteristics of robot)

	I do not feel anxiety at all	I hardly feel any anxiety	I do not feel much anxiety	I feel a little anxiety	I feel quite anxious	I feel very anxious
How robots will move	1	2	3	4	5	6
What robots will do	1	2	3	4	5	6
What power robots will have	1	2	3	4	5	6
What speed robots will move at	1	2	3	4	5	6

Participants were instructed: “You will probably find that you feel anxious about some of the statements, and do not feel the same about others, to varying extents. Please indicate your level of anxiety to each of the statements. There are no right or wrong answers, just give your first impression without taking too much time”

Table 10 Risk taking index [32]

	Never	Rarely	Quite often	Often	Very often
Recreational risks (e.g. rock-climbing, scuba diving)	1	2	3	4	5
Health risks (e.g. smoking, poor diet, high alcohol consumption)	1	2	3	4	5
Career risks (e.g. quitting a job without another to go to)	1	2	3	4	5
Financial risks (e.g. gambling, risky investments)	1	2	3	4	5
Safety risks (e.g. fast driving, city cycling without a helmet)	1	2	3	4	5
Social risks (e.g. standing for election, publicly challenging a rule or decision)	1	2	3	4	5

We are interested in everyday risk-taking. Please could you tell us if any of these statements have ever applied to you, now or in your adult past?

Table 11 Prior robot experience [24]

	0 times	1 times	2 times	3 times	4 times	5 times or more
How many times in the past one (1) year have you						
Read robot-related material (stories, comics, news articles, product descriptions, conference papers, journal papers, blogs)	0	1	2	3	4	5+
Watched robot-related programs (film, television, DVD, the Internet)	0	1	2	3	4	5+
How many times in the past ten (10) years have you						
Had physical contact with a robot?	0	1	2	3	4	5+
Attended robot-related events (lectures, exhibitions, trade shows, competitions)	0	1	2	3	4	5+
How many times in your life have you built or programmed a robot?*	0	1	2	3	4	5+

*With which robots do you have experience with, if any?

Participants were asked to indicate the level of agreement with the statements discussing their experience with robots

Table 12 Graphical signage effectiveness questionnaire 1 (adapted from [13])

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Did not see any signs
I found the signs confusing	1	2	3	4	5	6
I found the signs helpful	1	2	3	4	5	6
I found the signs of no use to me	1	2	3	4	5	6

Participants were asked to indicate the level of agreement with the statements discussing the signage available during the experiment (Fig. 7)

Table 13 Graphical signage effectiveness questionnaire 2 (adapted from [13])

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Did not see any signs
The sign assisted me in selecting how to operate the robotic arm	1	2	3	4	5	6
The sign reinforced my decision concerning how to operate the robotic arm	1	2	3	4	5	6
The sign made no difference to my decision how to operate the robotic arm	1	2	3	4	5	6
The sign assisted me to make a quick decision how to operate the robotic arm	1	2	3	4	5	6
The sign made me stop and hesitate a little while deciding how to operate the robotic arm	1	2	3	4	5	6

Participants had to indicate the level of agreement with the statements discussing how effective the signage was in its purpose to assist operation of the robotic arm

Table 14 Technology usage and programming experience questions

	0–5 h	6–10 h	11–15 h	16–20 h	21+ h
How many hours per week do you use computer for work/ assignments?	1	2	3	4	5
How many hours per week do you use computer for internet browsing/socialising?	1	2	3	4	5
How many hours per week do you play computer games?*	1	2	3	4	5

*What kind of computer games do you usually play?

Participants were asked to indicate their agreement with each statement

Table 15 Programming experience questionnaire

	Very inexperienced	Inexperienced	Neither experienced, nor inexperienced	Experienced	Very experienced
How do you estimate your programming experience?	1	2	3	4	5

Participants were asked to indicate their programming experience

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