Will Operators Work in Close Proximity to Industrial Robots? A Study of Acceptance Using Psychological and Physiological Responses.

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Abstract

Industry 4.0 and the introduction of human-robot collaboration offers manufacturing companies the potential for increased productivity and efficiency. However, robots can still be a concern for human operators. The present study aimed to investigate people’s acceptance of working alongside an industrial robot. Participants completed a drilling and measuring task in three experimental conditions: working close to the robot, working at a further distance from the robot and, as a control condition not measuring proximity effects, working without the robot operating. Physiological responses (skin conductance and heart rate) and eye gaze were recorded, along with self-report psychometric measures of trust, attitudes towards the robot, technology readiness, workload, situation awareness, and qualitative opinions relating to satisfaction. Results show little to no change in any of the self-reported psychometric measures between the experimental conditions, indicating that proximity had no effect on participants’ psychological states. However, in both of the experimental conditions examining proximity effects skin conductance levels were higher than in the control condition, indicating that arousal levels are increased by the robot simply being operational regardless of proximity. Results also suggest that participants evaluated their performance as better if they completed their task before the robot finished, which provides some insight into the potential dynamics of future human-robot partnerships and the need for collaborative tasks to be designed with care so that task cycle times suit requirements of both the robot and the operator.

Keywords: Human-robot collaboration; Technology acceptance; Trust; Satisfaction; Mental Workload

1. Introduction

The current shift towards promoting even closer collaboration between humans and technology in manufacturing, and the increased attention towards increasing the lifespan of manufacturing assets, raises the need for investigations of how human-robot collaboration can replace labour-intensive tasks. Collaborative robotics is a particularly prevalent and fast-developing manufacturing technology, with increasingly larger systems now being made safe for integration with human operators to perform heavier industrial tasks needed in sectors such as aerospace. The workforce will continue to play a key role when these tasks become shared with robots, and this shift provides work and upskilling opportunities for operators [1]. However, introducing robots into processes previously performed only by humans poses challenges for the operators’ psychological well-being and work efficiency. Changes to working methods that involve enforced collaboration and task sharing between robots and humans may be perceived as threatening in any environment. The main issues arise not only from technical aspects concerning the introduction of the robot, work cell or process characteristics [2], but also from various potential psychological impacts on human operators. These impacts might be particularly significant where workforces have previously been trained and enculturated to be wary of the physical risks posed by larger industrial robots.

A number of specific psychological impacts are known to be relevant in automated systems. For example, Mental Workload is notoriously affected by automation and associated with human performance and error problems and could, therefore, be affected by the demands of working collaboratively with a larger industrial robot. Similarly, Situation Awareness has also long been associated with automation impacts and is particularly important to work safety, with lower levels being linked to increased work accidents and
injuries [3], [4]. Repetitiveness and automated quality control in collaborative systems could reduce awareness. Trust and Acceptance of new systems are also psychological states that have long been associated with technology adoption and operational success. Trust is central to all human-robot interaction [5] and has been found an underpinning factor in new process adoption [6]. Acceptance could be affected if a new system diminishes operators’ sense of control and ownership which, along with high self-efficacy, has been related to increased acceptance and participation [5], [6]. If a new robot undermines operators’ concerns this may cause rejection and increased mental strain [7] which might lead to burnout [8]. Lack of Acceptance may also lead to greater monitoring of robot performance and Mental Workload, thereby reducing the cognitive capacity for monitoring other aspects of the environment and complying with safety procedures [9], [10].

Other psychological states and attitudes may also be important to this topic. A lack of human factors in the design and introduction of new systems is one of the leading causes of technology failure within the manufacturing industry [11]. However, studies have shown that human-robot collaboration in manufacturing can reduce human workload, improve efficiency of processes, enable the retention of key skills, and reduce dangerous manual work [12]. Furthermore, although past studies have explored how distance to the robot affect individuals’ sense of comfort around it [13], the current study fills the gap how this is reflected in manufacturing tasks. To sum up, it is important that new collaborative systems are developed to reduce impacts on the human operator but the nature of these impacts are currently unknown. To advance our understanding of potential impacts, the current study aimed to investigate how proximity to a large-scale robot may affect operator Acceptance and performance.

2. Methods

2.1. Design

A repeated measures experimental design was used to investigate the impact of proximity to an industrial robot in a close working condition (3.3 meters), a far working condition (5.5 meters), and in a control condition (robot not operational) on selected physiological and psychological measures that would reflect operator Acceptance: Mental Workload, Situation Awareness, Trust, Technology Readiness, Physiological measures of electrodermal activity (EDA) and heart rate (HR), and gaze fixation duration. Participants completed three separate trials.

2.2. Participants

Eighteen participants (12 males) with a mean age of 25.06 (standard deviation [SD] = 3.02) years old took part in the experiment. Two male participants did not complete all three sessions leaving sixteen participants (10 males) in the final analysis. This study was approved by the Cranfield University Research Ethics Committee, and conducted in accordance with the Cranfield Research Integrity Policy, the British Psychological Society’s Code of Human Research Ethics, and the General Data Protection Regulation 2018.

2.3. Equipment

As the scenario design was a collaborative drilling task, a Comau NM45 45kg industrial robot arm was equipped with a real drill end-effector. As real drilling was not required, this was activated only to simulate drilling actions and sound. To safeguard against injury from incursion into the robot’s work envelope / space, a light curtain surrounded the demonstrator cell. In addition, model components representing an aircraft leading edge rib section and a Vernier caliper were supplied for the task.

2.4. Measures

In order to capture participants subjective and objective response to the experimental conditions, a combination of physiological recordings, eye tracker and self-report questionnaires were used.

Physiological measures of EDA and HR were measured using a Shimmer3 GSR+ Unit bracelet, worn around the wrist of the non-dominant hand. Measures of gaze fixation duration were captured using SMI Eye Tracking Glasses and analysed using SensoMotoric’s BeGaze© software.

Psychological measures were captured using a range of psychometric scales to elicit quantitative administered after each trial. These data were supported by open-ended questions to elicit qualitative data to explain the factors that may have influenced satisfaction. The selected psychometric measures are as follows.

Technology Readiness was measured in this study to identify whether participants’ inclinations for using new technologies in general was affected
by proximity. The Technology Readiness scale [14] contains ten items for which participants indicate the extent to which they agree or disagree using a 5-point Likert scale ranging from “I strongly disagree” (1) to “I strongly agree” (5). The values are averaged to obtain one global score of Technology Readiness.

Situational Awareness was measured using the Situational Awareness scale [15] which consists of nine items to which responses are given on a 7-point scale ranging from “low” (1) to “very high” (7). The overall score is the average of all scores.

Mental Workload was measured via administration of the NASA-Task Load index (NASA-TLX; [16]) which consists of six factors: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration Level. For each of these dimensions, participants retrospectively indicate their experience along a scale ranging from “very low” (0) to “very high” (100). Results are computed by averaging all scores to present an overall Mental Workload score.

Trust in the robot was measured to explore how this particular robot drilling demonstrator affects participants’ confidence using the ten item Trust in Industrial Robot scale [17] which measures three context-specific dimensions: motion and pick-up speed, safe co-operation, and robot and gripper reliability. Participants indicated the extent to which they agree or disagree with each item using a 5-point scale ranging from “I strongly disagree” (1) to “I strongly agree” (5). As this experiment involved a drilling end effector, not a gripper, some items were reworded and one item was removed. The subscales were averaged for each dimension and then across all dimensions to produce the overall trust score.

Attitude towards robots was measured with the first subscale of the Negative Attitudes towards Robots Scale (NARS; [18]). Negative Attitudes toward Situations and Interactions with Robots. This comprises six items and participants indicate the extent to which they agree or disagree on a 5-point Likert scale ranging from “I strongly disagree” (1) to “I strongly agree” (5). The overall score is computed by averaging scores for all six items.

Satisfaction factors specific to this task were derived using four general open-ended questions:

- What contributed to you enjoying working alongside the robot?
- What contributed to you disliking working alongside the robot?
- What contributed to you disliking the task?
- What contributed to you liking the task?

Finally, questions to identify participants’ age, gender, and their previous experience of robots were presented at the end to avoid inducing a stereotype threat bias.

2.5. Procedure

Participants were first given a full briefing on the nature of the study and their ethical rights. They were then asked, if satisfied to continue, to sign the requisite informed consent form. Then, the Shimmer3 GSR+ Unit was strapped on their non-dominant hand and the eye-tracking headset was adjusted on their head and calibrated. The robot was then initiated to run through a demonstration cycle so that the participants could observe and familiarise themselves with, or be reminded of, its actions and sounds. Participants were ready to begin their manual task.

The task was to measure the diameter of the component holes using a Vernier caliper and record measurements on a printed A4 data sheet at a designated workstation table. The components already had eighteen drilled holes that had been numbered with a marker pen. Once a participant finished the three measurements, they had to wait for the robot to come to a complete stop. After the robot stopped, participants had to place the component they had just measured on another workstation table positioned outside the robot cell, then pick up a different component that was there and bring it the workstation table, which was inside the robot’s workspace, to be ‘drilled’ next. They then took the component the robot had just ‘drilled’ to be measured next as their task. When this swapping procedure was complete and the participant was ready to measure the newly ‘drilled’ component, participants informed the laboratory technician who started the robot for the next set of drilling. This process was repeated until participants had measured 3 holes in each of the 5 components.

When all five cycles of the task were finished, the eye-tracker and the Shimmer3 GSR+ Unit were removed and participants completed the questionnaires. Each trial lasted less than 45 minutes. Participants were then given a written and verbal debrief.
2.6. Analysis

Self-report psychometric data were investigated with repeated measures tests. After testing for normal distribution with the Shapiro Wilk test, the normally distributed data were analysed with parametric repeated measures ANOVAs or with their equivalent non-parametric Friedman ANOVAs. Further post-hoc comparisons were performed with paired t-tests (or using Wilcoxon Signed-Rank tests as the non-parametric equivalent).

Data recorded with the Shimmer3 GSR+ unit was automatically calibrated by its Consensus software. A two-minute baseline was recorded and the time points from when participants approached the testing area until they finished the session were used for the analysis. Skin conductance level was extracted from the EDA data, and Photoplethysmogram (PPG) signal used to derive heart rate via a bandpass filter.

The analysis of the eye tracker data focused on the timeframes when participants were looking at the robot. These were captured between participant completing their measurement of one part and starting on the next part. During these time frames, three Areas of Interest (AOI) were defined: assembly part, robot, and robot driller.

Across the analysis section, to account for the increased chance of type I error (false positive), a Bonferroni correction was applied to the threshold of significance (level of significance specified within each analysis). As the exact correction was changed between tests due to differing degrees of freedom this information is detailed in the Results section.

3. Results

3.1. Qualitative Data: Satisfaction Factors

Thematic analysis of the qualitative responses to the four open-ended questions exploring satisfaction produced key themes, as presented in Tables 1 and 2. Because participants in both close and far conditions tended to refer to both the task and the robot irrespectively of whether the question specifically asked about the task or the robot, responses to both were explored together.

Responses show that the mere presence of the robot itself was the most frequently reported theme related to enjoyment of the task / robot. When being more specific about the particular aspect of the robot that contributed to enjoyment, participants predominantly reported reliability and efficiency, as well as the novelty of the situation. Regarding the task, participants reported mostly enjoying its simplicity across all three conditions. Finally, in the control condition, the quietness of the session was mentioned as a positive factor. It is worth noting that all three participants who reported quietness did so for their third and final session, after already experiencing two sessions in which the robot was running.

| Table 1. Frequency of reported themes related to the participant enjoying the task / robot |
|-------------------------------------------------|--------------|----------------|----------|
| Presence of the robot                           | Control      | Far            | Close    | Total    |
| Efficiency                                      | 9            | 9              | 7        | 18       |
| Robot                                           | 2            | 5              | 7        | 14       |
| Reliability                                     | 3            | 3              | 6        | 12       |
| Novelty of situation                            | 3            | 1              | 4        | 8        |
| Task                                            | 2            | 3              | 4        | 9        |
| Simplicity of the task                          |              |                |          |          |
| Silence/quietness                               |              |                |          |          |
| Total                                           |              |                |          |          |

Regarding factors that contributed to participants’ dislike of the task or robot, a frequent answer was the waiting time involved when they had finished measuring the three holes of the component and had to wait for the robot to finish its drilling of the next component. One participant reported feeling as if they were in competition with the robot, whilst another reported that working and finishing simultaneously with the robot was a factor that they enjoyed. Another common answer referred to the drilling noise being too loud, particularly in the close condition. Regarding the task, the most common answer given with equal frequency across all three conditions referred to the task being boring or too repetitive. Finally, several participants, particularly in the far condition, reported that there was nothing they disliked during the session.

| Table 2. Frequency of reported themes related to the participant disliking the task / robot |
|-------------------------------------------------|--------------|----------------|----------|
| Waiting for the robot robot to finish its task | Control      | Far            | Close    | Total    |
| Noisiness                                       | 4            | 7              | 7        | 11       |
| Task                                            | 6            | 6              | 6        | 18       |
| No dislike                                      | 1            | 9              | 2        | 12       |

To investigate whether distance to the robot affect psychological factors, one-way ANOVAs were performed with the independent variable being experimental condition (close proximity, far proximity and no robot condition) and the dependent
variables being self-report measures. Only Mental Workload data showed significant differences between experimental conditions. Other measures did not reach significance ($F \leq 2.695, p \geq .085$).

3.2. Mental Workload

A non-parametric repeated measures Friedman ANOVA was conducted with dependent variables being the Mental Workload ‘Factor’ (Mental Demand, Physical Demand, Temporal Demand, Effort, Performance and Frustration) and the independent variable being the ‘Condition’ (close, far and control). The main effect of Factor was significant ($\chi^2(5, 17.15) = 65.49, p \leq .001$), but the main effect of Condition and the interaction between Condition and Factor were not significant ($\chi^2(2, 15.70) \leq 1.30, p \geq .300$).

To test whether overall Mental Workload differed between conditions, a repeated measures ANOVA was conducted. The result ($F(2, 30) = 0.649, p = .530, \eta^2 = .041$) did not reveal any significant effect of the perception of Mental Workload.

Further investigation of the main effect of Factor was conducted with the Wilcoxon Signed-Rank test for paired measures. The results of the test statistics show that Effort was rated significantly higher compared to Mental, Temporal, Physical Demand, and Performance (Table 3).

Table 3. Descriptive statistics and paired comparisons between NASA TLX factors

| Factor        | Mental Demand (MD) | Physical Demand (PD) | Temporal Demand (TD) | Effort (E) | Performance (P) | Frustration (F) |
|---------------|--------------------|----------------------|----------------------|------------|-----------------|-----------------|
| N             | 15                 | 15                   | 15                   | 15         | 15              | 15              |
| Mean          | 32.33              | 29.44                | 27.67                | 82.67      | 31.89           | 16.22           |
| SD            | 24.32              | 21.76                | 15.68                | 15.18      | 14.65           | 12.17           |
| PD            | 0.49               |                      |                      |            |                 |                 |
| TD            | 0.41               | 0.06                 |                      |            |                 |                 |
| E             | 3.41*              | 3.41*                | 3.41*                |            |                 |                 |
| P             | 0.49               | 0.06                 | 0.99                 | 3.41*      |                 |                 |
| F             | 2.16               | 1.61                 | 2.36                 | 3.41       | 2.53            |                 |

*p < .001, (Bonferroni correction for multiple comparison $p = .003$)

3.3. EDA and HR

To investigate whether proximity to the robot had an effect on participants’ physiological data, a non-parametric Friedman ANOVA was performed and results showed that EDA response was significantly affected by distance to the robot ($\chi^2(2) = 9.73, p = .008$). HR, however, did not significantly differ between conditions ($\chi^2(2) = 3.73, p = .155$).

Further investigation of EDA results with a Wilcoxon Signed Rank test showed that in the close proximity condition EDA was significantly higher compared to the control condition ($Z = 2.05, p = .04$), and the difference between the far and control conditions was almost significant ($Z = 1.89, p = .059$). However, after a Bonferroni multiple comparison correction (two-tailed alpha = .016), these differences were not significant. The difference between the far and close conditions did not show a significant difference ($Z = 0.18, p = .859$).

3.4. Eye Tracker

To analyse the eye tracking results a 3 x 3 repeated measures ANOVA for a non-parametric test (3 experimental conditions (close, far, and control) and 3 AOI) were constructed. The results show the main effects of Condition and of AOI were both significant ($\chi^2(2, 13.15) = 6.90, p \leq .009$ and $\chi^2(2, 14.74) = 44.85, p \leq .001$) as well as a significant interaction between Condition x AOI ($\chi^2(4, 14.96) = 3.43, p \leq .035$).

Further investigation of gaze fixation duration on AOI results was performed with a Wilcoxon Signed-Rank test. The results confirm that participants were looking at the robot driller more in the far and close conditions than in the control condition ($Z = 2.98, p = .003$ and $Z = 3.41, p = .001$, respectively; Fig. 1) but the difference in gaze duration between the far and close conditions was not significant ($Z = 0.06, p = .955$). In addition, fixation duration towards the assembly part was significantly longer gaze in the control than in the far condition ($Z = 2.93, p = .003$), but not when comparing control vs. close or close vs. far conditions ($Z = 1.82, p = .069$ and $Z = 0.16, p = .875$, respectively).

Regarding gaze duration towards each of three AOIs across conditions, the close condition results showed a significantly greater gaze fixation duration towards the assembly part vs. robot or vs. driller ($Z = 2.98, p = .003$ and $Z = 3.41, p = .001$, respectively). Yet, no significant difference was found between
gaze fixation duration towards the driller and robot AOI (Z = 0.284, p = .776). The same pattern was observed in the far condition: significant differences in the assembly part vs. driller or vs. robot (Z = 2.95, p = .003 and Z = 3.07, p = .002, respectively) and no significant difference between driller vs. robot (Z = 0.85, p = .394). Finally, in the control condition gaze fixation duration differed between all three conditions; assembly part vs. driller (Z = 3.41, p = .001), assembly part vs. robot (Z = 3.35, p = .001) and driller vs. robot (Z = 3.30, p = .001). Figure 1 shows heat maps depicting the average fixation times across experimental conditions: (A) close, (B) far, (C) control, and (D) the percentage of gaze duration over AOI across the conditions.

Figure 1. Gaze fixation heat maps and % AOI duration

3.5. Correlation between measures

To test how the self-report psychometric data, physiological data and eye tracking data might be related, correlation analyses for each condition were conducted. As physiological measures were not normally distributed, the Spearman rho correlation coefficient was used. A significant negative correlation was found between EDA and the Physical Demand factor (NASA-TLX): rho(15) = -.610, p = .016. A positive significant correlation was found between EDA and Technology Readiness (rho(14) = .647, p = .012) and between EDA and the Frustration factor (NASA-TLX) at a trend level, rho(15) = -.455, p = .088. Other correlations were not significant (rho(15) ≤ .407, p ≥ .132).

The equivalent analysis in the far robot condition did not show any significant correlations (rho(15) ≤ -.321, p ≥ .243). The control condition, however, showed a significant negative correlation between HR and Mental Demand (NASA-TLX) (rho(15) = -.613, p = .015). Negative correlations approached significance between EDA and Mental Demand, and between EDA and Physical Demand (NASA-TLX), (rho(15) = -.513, p = .051, and rho(15) = -.488, p = .065, respectively). A negative correlation at a trend significance was observed between HRV and Physical Demand (NASA-TLX) (rho(15) = -.459, p = .086). The remaining correlations were not significant (rho(15) ≤ .391, p ≥ .150).

Finally, eye tracker fixation measures were correlated with self-report questionnaire data. Similarly to the above reported results, significant results were only found in the close and control conditions. In the close condition, there was a significant negative correlation of the Performance factor (NASA-TLX) with the robot AOI (rho(15) = -.641, p = .010), also a positive correlation approaching significance was found with the Effort factor (NASA-TLX) and the end effector AOI (rho(15) = .495, p = .061). In the control condition, Temporal Demand (NASA-TLX) positively correlated with the end effector AOI (rho(15) = .532, p = .041), and there were trend significance negative correlations between Situation Awareness with the robot AOI (rho(15) = -.470, p = .090).

4. Discussion

This study aimed to identify factors that are likely to influence operators’ acceptance of working near to an industrial drilling robot by measuring a range of physiological and psychological responses when performing a task in three experimental conditions: close to a working robot, far from a working robot, and, as a control, without the robot moving. The multifarious response data were analysed using a range of procedures. However, only Mental Workload was significantly affected as participants rated their Effort on the tasks significantly higher than Mental Demand, Physical Demand, Temporal Demand and Performance. This indicates that an operational industrial robot stimulates monitoring and increases cognitive effort. The EDA and HR results, although not significant, also show that higher physiological arousal occurred when participants were working with the robot compared to the control condition when the robot was not operational. This may be due to participants experiencing negative responses, such as more anxiety or mistrust towards the robot, but identifying the nature of the arousal will require further exploratory research.

Correlation analysis presented a significant negative correlation between EDA and Physical Demand in the close condition as well as a negative correlation between HR and Mental Demand in the
control condition. As skin conductance typically reflects physiological arousal, a positive relationship had been expected. A significant positive correlation between Technology Readiness and EDA suggests that if participants were experiencing physiological arousal and possibly anxiety during the task, but successfully completed it, their confidence would increase acceptance and participation. The qualitative results can provide some support for this notion as most participants reported that the robot’s presence contributed to their enjoyment.

The positive relationship between gaze towards the robot AOI and the Performance Mental Workload factor suggests an association between participants’ evaluation of their own performance and the number of times they looked at the robot when in close proximity. As participants disliked having to wait for the robot and felt more enjoyment from finishing simultaneously or before the robot, there appears to be a relationship between satisfaction and perceived performance which is enabled by real task time. These indications are important because although the robot’s speed has to be limited in a shared workspace for safety reasons, the perception of ‘slowness’ and the need to wait may cause frustration and dissatisfaction which could have wider impacts on human and system performance. As this study shows, not all individuals work at the same pace and some may find enjoyment from team working aspects such as parallel task performance and competition. Therefore, it is going to be important to optimise the speed of systems to not only ensure operator safety on the one hand but to stimulate operator satisfaction and motivation on the other.

A key limitation of the current study and its findings is its participant sample; this is very likely to have contributed to lack of significance across many of the results. First, the sample size was very limited, which may explain borderline or near-significance results, particularly as the study involved so many variables and a repeated measures longitudinal design. Larger datasets may well have provided a clearer picture or even achieved significance in some results. Second, the constitution of the sample was limited to volunteers who were all directly linked to technology-related studies and careers at the university. This means participants are likely to be biased towards positive attitudes and confidence in new technology and robotics. Further studies need to be designed to recruit a larger and more diverse sample, which would facilitate more repeated trials and longitudinal value.

Another limitation was that although there was an observed correlation between the physiological and self-report psychological measures, the qualitative data collection in this study was not sufficient to explain results. In particular, the small number and generality of the open-ended questions were not able to clarify the unexpected and counterintuitive results that this study generated. Further studies should, therefore, incorporate a greater degree of qualitative data collection via a carefully designed survey or structured interview questions that are linked directly to the dependent and independent variables and explain individuals’ experiences.

5. Conclusions and Future work

In conclusion, the current study provides evidence of future research directions needed to improve future collaborative human-robot applications. Working in close proximity to a robot appears to not only increase mental workload and time pressure, but also satisfaction and perceived performance. It appears that, rather than proximity itself, a key design issue will be to achieve the correct task cycle time to suit operators and ensure this is balanced with the robot task speed. This is in particular important in the manufacturing of long-life engineering assets such as planes, ships, and heavy machinery where collaborative robotics are being introduced alongside the human workforce to increase the efficiency and precision of the production. As a result, it is expected that this will improve the life of products. This implementation will only be successful if increased human workforce satisfaction and well-being is accounted for. The current study suggests that operators working with technology which can adjust to their optimal working speed, or possibly even be customisable depending on their needs can increase the speed, accuracy, and satisfaction of production.

Yet, to measure the full impact of robot working speed on operator’s well-being, future research should aim to identify optimal task performance times and synchronisation between the human and robot partners. In particular, further investigation is needed to determine how the physical and mental well-being of manufacturing operators alters with changes in robot speed either matching operator’s speed vs. being quicker or slower. Future studies should also look into longitudinal effects of working in collaboration with robots and whether customisation of the speed by the operators themselves could result in increased production efficiency.
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