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“We Don’t Need Ergonomics Anymore, We Need Psychology!” – The Human Analysis Needed for Human-Robot Collaboration

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ABSTRACT

Human labour has always been essential in manufacturing and, still, no machine or robot can replace innate human complex physical (dexterity) and cognitive (reasoning) skills. Understandably, industry has constantly sought new automation technologies and largely only concerned itself with physical health and safety issues to improve / maintain production processes, but these industrial engineering approaches have largely overshadowed our understanding of wider social and emotional issues that can also significantly impact on human-system performance and wellbeing. In the current climate, industrial automation is rapidly increasing and crucial to manufacturing competitiveness, and requires greater, closer human interaction. Consequently, people’s cognitive-affective abilities have never been more critical and there has never been a more important time to thoroughly understand them. Moreover, industrial engineers are themselves now more aware and interested in understanding how people can better perform tasks in collaboration with intelligent automation and robotics. This paper describes why industry is only now realising the need for psychology, how far research has advanced our knowledge, and how a major UK project is working to develop new human behaviour models to improve effectiveness in the design of human-robot interactions in modern production processes. As one recent anecdotal comment from a UK industrialist set out: “we don’t need ergonomics anymore – our industrial engineers can do that, we need psychology”!

Keywords: Human-robot collaboration, Human-robot interaction, Human-systems integration, Cognitive ergonomics, Industrial psychology, Industrial robots, Technology acceptance

INTRODUCTION

Our knowledge of what enhances human-robot interaction in manufacturing systems is still in its infancy, and the importance of gaining this understanding is still being realised. This may be surprising to some, given the enormous salient advances in technology, robotics and AI that have already touched all of our lives, and the huge amount of research and development work that has already been conducted. How to prevent immediate physical injury is understood very well, but progress toward understanding how people behave and respond to industrial robots in other more subtle and enduring ways has been overshadowed by two stronger areas of interest: a long 'technology focus' which prioritised development of machines and automation rather than human interactions, and a 'classical ergonomics' approach which prioritised attention to physical risks and outcomes rather than cognitive responses and psychological well-being.

Although we are still in the midst of the 4th technology-driven industrial revolution of digitisation, we already facing 'Industry 5.0' which is said to be more 'value-driven' (Xu et al., 2021) consider wider human impacts such as skills, values and ethics within "a growing consciousness of the value of a human-machine symbiosis in industry" (Longo et al., 2020), the focus now needs to shift towards the human element.

This paper explores the current problem where psychological knowledge is now greatly needed but its development has been fundamentally obstructed by a traditional prioritisation of technology development, and a tension between classical (physical) and cognitive ergonomics. It begins by presenting the historical background to the current situation in terms of both the focus on technology and physical human analysis, then explains the progress of automation and its growing need for psychological science, and finally the work of a major new UK initiative to develop and integrate this body of knowledge before conclusions are summarised.

BACKGROUND

Technology Focus

During the first industrial revolution, the enhanced productivity and reliability offered by new machinery began an enduring 'Machine School' of thought that sought to replace manual work wherever possible (Doyle, 2003). Human labour was considered costly and unreliable due to variability, so machines were seen as the cheaper and more reliable future. Although various physical and psychological difficulties became apparent when manufacturing work became centralised, simplified, and interspersed with machinery during this period of industrialisation, the drive to further develop and automate production remained paramount.

In the early 20th century, industrialists also attempted to tackle human variability by developing time and motion work study methods to identify and reduce unnecessary human activities. This 'division of labour' allowed jobs to be split into smaller tasks to reduce labour, training costs and inefficiency, and allow some tasks to be allocated to machines. Time and motion work study also offered engineers a way of applying *"scientific and engineering criteria to the human sphere as they had to the mechanical"* (Watson, 1995, p. 44) which reflects an industrial preference for empirical and quantitative methods. Indeed, as it is the innate variability of human beings that obstructs prediction of their behaviour, the systematic and generalised approach of work study methods made human analysis more acceptable.

Industry continued to give precedence to the development of technology and the use of engineering approaches within an ambition for 'lights out' manufacturing: fully automated without direct human inputs for production tasks. For example, as a direct result of technological advances, USA industrial power derived from machines rose from 14% to 80% between 1850 and 1950 (Argyle, 1992). However, whilst this prioritisation of technology has led to many industrial successes, attention to the human issues that can also make the technology successful have been largely neglected. Workers' cognitive and affective responses can be a major influence on the overall performance of a manufacturing system (Fletcher et al., 2003), and insufficient consideration of them has been a root cause of failed manufacturing technology implementation (Chung, 1996).

How Physical Analysis Overshadowed Cognitive Factors

It was not until World War II that the scientific field of Ergonomics formally emerged, when the new war technologies demonstrated that performance relied on a good fit between machines / systems and human capabilities (Swain, 1990). Ergonomics emerged to match people with their surrounding environments more effectively and to some extent this included applications of psychology to understand cognitive processes and behavioural responses. However, in the manufacturing sector, work systems have always been designed to meet technical product and process requirements first and foremost. The implications of human issues and behaviours have usually been a secondary, late-stage consideration in the process of manufacturing system design (Fletcher et al., 2003) usually to address physical risks and position people to suit technical requirements and avoid costly workforce injuries, not psychological impacts.

The traditional ergonomic focus on physical factors is understandable given the nature of early technology and industrial relations. Industrial machines have always mostly been developed to replace manual work, and the hazards they most immediately pose tend to be physical harms, so it is natural that physical issues were prioritised. In addition, management-workforce relations in industry have often been difficult and divided, so any notion of psychological analysis would likely spark worker mistrust and negative reactions, whereas physical analyses give rise to little sensitivity.

Hollnagel (1997) notably described this approach as 'classical ergonomics', which may also be associated with 'industrial ergonomics' or 'occupational biomechanics', and the need for measurement in Western empiricism. In this respect, the systematic and quantified measures of 'classical ergonomics', and indeed work study methods, has also aligned with industrial engineering principles and is now a standard element of industrial engineering design methodology which reinforces the dominance of physical analysis.

Cognitive Ergonomics

As time and technology has advanced, so has the need for a better understanding of psychological aspects of human-system interactions. Hollnagel's 1997 definition of 'classical ergonomics' was put forward to represent physical analysis in contrast to 'cognitive ergonomics' which is: *"oriented to the psychological aspects of work both in how work affects the mind and how* *the mind affects work*" (Hollnagel, 1997, p. 1171). This is recognition that the nature of work was transitioning from jobs that primarily needed physical strength, endurance, and dexterity to new technology-driven jobs that require cognitive skills for attention, problem-solving and reasoning. It was also recognition that cognitive analysis / psychology was now needed (and embodied in the discipline of 'human factors').

In the 25 years since Hollnagel's paper was published technology has, of course, continued to advance and influence the way jobs are performed. Today, people engage with various digital and automated systems as part of their everyday lives and work and, in most cases, this presents no problem as the interaction is often relatively innocuous and superficial, and people can familiarise naturally. However, when new technologies are more impactful or intrusive in any way it is much more important to ensure they are designed well, to ensure safe and effective use and engagement. The higher levels of interaction that modern technologies demand inevitably bring a higher demand for psychological engagement as people are now not simply required to perform tasks amongst machines but in direct interactions with them. This means it is no longer a case of simply matching the respective functions of machines and humans, but of ensuring they can communicate and cooperate effectively in working partnerships. New technology adoption is largely determined by the level of engagement of intended users, so to ensure new systems are successful it is crucial to promote that engagement.

Clearly, there is a need for greater understanding from a cognitive ergonomics perspective, and research studies have incorporated more attention to human cognitive and affective responses to new technologies. However, there remains an obvious gap between technology development and its integration of human science, and particularly psychology. Most of the vast array of studies in this area have been conducted from a limited engineering perspective that does not include valid and reliable social science methods or psychological measures. Thus, to date, there is still little verified knowledge or unified data that tells us how best to design and implement human-system interaction. For example, technologies are typically designed to be assistive with an ambition to reduce human workload. However, reducing workload is not always ideal (if it reduces attention below the optimal level) and in many cases automation can cause the opposite and increase workload / reduce awareness (Parasuraman et al., 2008). So, in the age of the fourth / fifth industrial revolution we clearly need to apply psychology to better prepare for the sharp and quickening rise in workplace automation.

Industrial Human-Robot Collaboration

Automation has long been the key driver of mechanisation in the manufacturing industry and robots epitomise the industrial ambitions to reach fully automated 'lights out' manufacturing. Indeed, it is predicted that over 60% of machine operators' and assemblers' current tasks will be automated by 2030 (Hawksworth et al., 2018). Complete automation of production processes, however, is rarely feasible because it is still not possible to replace human capabilities, such as decision making and dexterity in assembly tasks

(Shen et al., 2015), and supervision and maintenance of technical systems and machines (The Economist, 2012). Industrial robots provide the strength and speed that is ideal for simple, heavy and repetitive tasks that are monotonous or unhealthy for humans and have mostly been developed to replace physical/manual activities (Hawksworth et al., 2018). However, the problem is that people are still needed for their cognitive reasoning and fine motor skills in more complex production tasks, but the strength and speed of 'traditional' heavy robots has meant they have needed complete segregation from the workforce, contained behind physical guarding or laser barriers (typically upstream) to prevent injury. This separation creates an obstacle to production efficiency because it prevents robots from being positioned in places where they are also needed for simple, heavy and repetitive tasks further downstream (alongside operators), and disrupts flow and flexibility (Hedelind and Kock, 2011). Consequently, human skill is very often wasted on executing unhealthy tasks that would be better suited to a robot, while robot strengths are not applied where they would really help and release human skill for more complex tasks elsewhere. The ideal solution, therefore, is to safely integrate human operators with industrial robots to work together collaboratively in the same space, allocating tasks to best exploit their respective skills and talents.

Human-robot collaboration (HRC) has been made possible in recent years by advances in sensors and safety control technologies which can monitor systems and limit or deactivate operations if safe conditions are interrupted. These technologies have enabled the creation of many low-payload, power and force-limited (PFL) robots specifically for collaboration involving 'light' tasks. However, given that a key benefit of industrial robotics is to take on fast and heavy production tasks, an important outcome of these new technologies is that they can be integrated with 'traditional' larger payload robots to provide an additional layer of protection as a unified system. Thus, if these safety controls are integrated to monitor and activate protection it is now entirely possible for any robot to be made safely collaborative.

HRC helps satisfy two key contemporary production requirements: system flexibility and workforce skills diversity. Flexibility is needed to meet fluctuating consumer demands for smaller batch customisation and the production reconfigurability that involves. Skills diversity is needed to accommodate the wider variations in workforce capabilities that are naturally arising due to increased population mobility, but also to enable the aforementioned consumer-led production change flexibility. HRC enables task steps to be allocated between the human and robot to deal with changing production requirements and skill variations with less system disruption and worker training. HRC is the solution to getting the best out of both people and robots, improving the synchronisation and sequencing efficiency of production processes whilst also maintaining human skills and employment (Favell et al., 2007). HRC means that industrial robotics will not replace human skills but will relieve people from alienating and potentially injurious tasks and provide opportunities for them to contribute more meaningful and "value-added work" (Unhelkar et al., 2014). However, we know that to achieve the benefits of HRC it is essential to consider new workforce requirements.

HRC not only requires the human to possess technical skills to perform tasks with a robot, but also a range of 'non-technical' skills needed for interaction and communications (Nahavandi, 2017). Of course, workers have always needed to interact effectively with human colleagues, but interactions with robotic team-mates may require different types or applications of social skills. For example, the level of trust that is absolutely critical to effective human-robot interactions is not only a function of a person's own characteristics and beliefs, it is also determined by robot-specific factors (Nahavandi, 2017), such as gripper reliability, speed and motion, and safe co-operation (Charalambous et al., 2016). Clearly then, these factors and their impacts need to be identified and designed for.

Industry's historical tendency to develop automation to alleviate physical activity but neglect to understand the psychological factors that are important for successful adoption and operation means new processes may end up not being used as intended, or not used at all. Industrial HRC systems are now vulnerable to this situation; highly effective automation solutions are being produced but our understanding of how best to design and implement them to suit, and get the best out of, human users is not fully grasped. Resistance to change is a barrier to adoption (Sharma et al., 2023), so what is the best way to introduce HRC work and promote adoption? How should HRC systems be designed to optimise human interaction and engagement? What aspects of HRC design will improve well-being? What skills or training do humans need to collaborate effectively? As discussed, there is a need for psychology now, to provide us with empirical scientific human data that will tell us how to design and install HRC to optimise human responses.

THE UK SMART COBOTICS CENTRE

In terms of industrial robot density and installation rates, the UK falls a long way behind many other countries (IFR, 2022), and the UK Government's The Department for Business, Energy and Industry Strategy (BEIS) recently encouraged organisations to spend more on new systems to boost the national economy (The Manufacturer, 2023a). Several countries with similar GDP to the UK (10%) show higher productivity rates due to their greater investment in industrial automation (The Manufacturer, 2023b). Key organisational barriers to the acquisition of new robotics include concerns about gaining workforce acceptance, lack of knowledge and new skills requirements (Kildal et al., 2018; Aaltonen and Salmi, 2019; The Manufacturer, 2023a). As there is no evidence to suggest any other countries have gained a better understanding of the factors that promote acceptance, knowledge or skills, this is unlikely to be the reason for the UK's lag. Given the current ascent of industrial robotics worldwide, it is certainly an apt time to establish this knowledge.

The 'Smart Cobotics Centre' is a four-year government funded project involving multiple UK academic and industrial partners and co-investors which aims to deliver new knowledge and capability for industrial HRC. The Centre has been developed to address four 'Priority Areas' (PAs), as follows.

Priority Area 1: Effective, Natural and Safe Human-Robot Collaboration

To achieve effective, natural, and safe HRC, systems need to be designed to achieve naturalistic, intuitive and seamless interactions. For this, designers need to be able to predict how people naturally interact with robots and other actors in a system and truly collaborate with them to fully leverage their respective strength. The PA1 programme of work will involve a suite of experimental studies to decode the causal interactions between people, objects, and their environment in the context of time, space, task and robot type differentials. This will enable us to ascertain behavioural rules and tendencies, so that we can model and predict human cognitive-affective behaviour over time and situations (normal and non-normal), predict risks and perturbations, and adjust human-system responses with deep understanding of the impact on human states. The specific deliverables from PA1 will be:

1. Probabilistic object-affordance models for complex industrial workspaces.
2. Large integrated temporal, spatial and cognitive state data sets from a wide range of industrial HRC tasks: empirical data.
3. Lifelong human intention prediction model based on real-time object-affordances and deep cognitive human state tracking.
4. New learning from demonstration, shared control and remote interaction methods based on predicted human-intention.

Clearly, these deliverables rely on development of a comprehensive empirical human cognitive-affective dataset, built up from numerous studies involving a wide range of conditions and situations. Experiments are due to begin imminently. We believe this will be the most extensive programme of HRC experimentation ever conducted, and will lead to the largest unified predictive HRC model.

Priority Area 2: Autonomous Dexterous Manipulation of Complex Components in Complex Workspaces

PA2 is designed to address the need for automation with more human-like dexterous manipulation and assembly skills to manipulate more non-rigid and varied shaped objects / tools while adapting to new and changing situations with minimal human intervention. Industrial robot capabilities have always been limited to very basic manipulation skills and simple objects. Modern manufacturing processes are increasingly in need of robots that possess more human-like manipulation skills for more complex assemblies involving non-rigid and composite materials, while adapting to evolving demands and changes with minimal human intervention. PA2 aims to address these requirements by exploiting the latest state-of-the-art robotic technologies to create new HRC intelligent and adaptive handling capabilities that are suitable for more difficult to manage objects and collaboration with humans. The PA2 deliverables will be built from technical rather than human-centred data:

5. A toolkit of adaptive and soft sensorised gripping technologies for handling compliant, varied and complex composite objects.
6. Intelligent adaptive planning and manipulation control methods suitable for unstructured and non-stationary environments.
7. Smart and sensorised soft manipulators with integrated sensorimotor control algorithms delivering dextrous and adaptive manipulation.

Priority Area 3: Rapid Design, Validation and Deployment of Smart HRC Systems

To address contemporary industrial needs for greater flexibility and diversity, processes for designing, verifying, validating, deploying and operating automation need to become more accessible for a wider range of people and organisations. Systems not only need enhanced manipulation capabilities as set out above, they need to be able to move quickly between low and high-volume production, be adaptive to move between different work modes (automatic, collaborative or remote), and be able to recover quickly and automatically to any disruptions. To achieve these requirements, PA3 will utilise and combine a range of techniques, technologies and testbeds in novel ways to generate the following set of deliverables:

8. Closed-loop in-process (CLIP) HRC digital twin with capabilities for high-fidelity testing, validation, analysis; and, constant real-time feedback.
9. Cloud-based database and computing platform to build and improve trust in HRC systems (incl. legal principles on data, privacy, health and safety).
10. Augmented decision studio for HRC systems with digital twin, augmented and virtual reality technologies and avatars.
11. Verification and Validation analysis and scenarios generation of HRC systems for stochastic behaviour and minimize risks.

Priority Area 4: Societal and Cultural Change Through Smart Automation

Automation has the potential to significantly enhance production processes and competitive advantage by transforming the way work is done and, as discussed, HRC is the solution to combining the inimitable strengths of humans and advanced robotics. However, even the most sophisticated and practical technology will fail if not designed and installed to meet the expectations and requirements of users, stakeholders, and their surrounding cultural environments. Therefore, to maximise HRC success it is not only crucial to improve immediate HRC interactions; we also need to develop the strategic policy and skills development infrastructures that will enhance wider, long-term acceptance, sustainability and growth (Sharma et al., 2023). To gather the knowledge needed to promote wider acceptance and successful adoption, PA4 will seek to identify the complex interactions between internal and external factors that affect how people perceive and respond to HRC and the new ways of working that will bring via the following deliverables:

12. A framework to engage multiple stakeholders in the introduction of safe, acceptable, and efficient introduction of new HRC systems.
13. A multiple stakeholder training and skills map to develop processes for building capabilities in optimal installation and operation of new HRC.
14. A roadmap for continuous engagement with stakeholders in continuous review and update of socio-economic factors for HRC.

As with PA1, the PA4 programme of work will rely on extensive human-centred data, built up from several studies. It will require not only canvassing the expectations and requirements of direct HRC users (human operators in factories) it will also need examination of views from other stakeholders in society. It is crucial to gather a reliable understanding of societal and cultural impacts, existing regulation and policy, ethical frameworks, and multidimensional requirements of emerging jobs and future skills.

To date, a wide-scale Delphi study has begun to canvass expert opinion on the ethical implications that need to be considered regarding rising industrial HRC working practices and potential consequences. Additionally, work to identify legal and regulatory issues is underway. Together these studies form part of a top-down approach to garner data from multiple stakeholders and experts on the wider social and societal issues that need to be considered. At the same time, a parallel bottom-up approach is being taken via a large survey of UK manufacturing workers.. Manufacturing workers have previously shown positive attitudes towards new technology and robotics (Leekasul et al., 2022) so this study will capture expectations and skills requirements, and measure current levels of work-related psychological and affective states such as satisfaction, commitment, motivation. Initial findings of all of this work are due to be collated by the end of 2023 and we anticipate findings will create the most comprehensive and unified predictive HRC behavioural model.

CONCLUSION

It is clear that the manufacturing industry is, once again, facing a period of rapid technology-driven revolution which will transform many of the manual methods and practices that have been in place for many years. The positive outcome will be that human work will not only be sustained but made more beneficial and meaningful, as robots will take on the unhealthy and monotonous tasks so that people can do the more safe and interesting jobs. However, this will involve close and collaborative interactions between people and robots of varying type and task. So, to ensure HRC transformations are successful it is critical that a solid and reliable understanding of how to optimise acceptance, adoption and operation of new systems is attained. It is vital that the imbalanced priority of technical development and neglect of psychological analysis in system design is now redressed; industry itself is now realising this.

The UK's new Smart Cobotics Centre is endeavouring to tackle this increasingly important industrial need. Two (of its four) research priority areas reflect the new psychological paradigm needed for HRC research. The work in PA1 will address the need for empirical knowledge regarding human-robot collaboration and interaction for system design purposes. PA4 tackles the wider socio-economic, socio-legal, and socio-ethical issues that will enable appropriate longer-term infrastructures to be put in place.

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