Positive and Negative Reinforcement Nudges for Human-Robot Collaboration using a Mixed Reality Interface

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ABSTRACT

The recent emphasis on the concepts of well-being, inclusivity, and sustainability as key topics in the human-centric design of manufacturing processes has brought about a significant transformation in the relationship between humans and machines within the manufacturing environment. The application of nudging, which involves influencing people's behaviour without restricting their choices, has been extensively explored in the healthcare and retail industries. However, in the manufacturing sector, very little has been explored, it is therefore necessary to identify appropriate nudging techniques that align with the behaviour of workers. Hence, this study presents a research endeavour aimed at investigating the effectiveness of smart nudges in the manufacturing industry. To achieve this, we will investigate a human-robot collaborative assembly process where workers are nudged throughout the process to improve their performance, safety, and well-being. The objective of this research is to determine how individuals respond to different delivery methods and techniques employed in creating these nudges. The experiment will involve the utilisation of mixed-reality headsets as a means to deliver the nudges to the workers. The outcomes of this research will contribute to the implementation of effective and beneficial nudges that facilitate human-robot collaboration.

CCS CONCEPTS

• **Human-Computer Interaction**; • **Human computer interaction**; • **(HCI) Interaction paradigms**; • **Mixed / augmented reality**; • **Collaborative interaction**;

KEYWORDS

Mixed-reality, Nudging, Industry 5.0, Human-Robot collaboration, Inclusive, Assembly-task

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1 INTRODUCTION

In recent years, the integration of human-robot collaborative systems into various manufacturing processes has become increasingly prevalent, spanning from the automotive shopfloors to the electronics production industries [1]. While robots possess remarkable capabilities in terms of speed and precision, seamless and effective collaboration requires careful consideration of the human element, emphasizing intuitive and efficient modes of communication. Therefore, it is imperative to ensure that these collaborations are not only efficient but also inclusive and conducive to positive human experiences and behaviours that enhance the collaborative process. Nudging presents a promising approach in fostering seamless and effective human-robot collaboration. By subtly guiding human behaviors and decisions, nudging can enhance intuitive and efficient communication between humans and robots. Nudges, as described by King [2] are subtle interventions that steer human behaviour in desired directions without resorting to coercion or restricting their freedom of choice. They operate on the premise that humans are not always rational decision-makers and can be influenced by environmental cues and contextual factors [3], whether these influences are intentional or not. Therefore, by strategically designing choice architectures, nudges can steer individuals towards making decisions that are in their best interests or align with predetermined goals.

In the context of HRC, nudges can be strategically employed to enhance human-robot collaboration and optimise teamwork. This could be achieved if nudges are leveraged to offer a means to shape behaviours and interactions in ways that enhance productivity, safety, and well-being. However, the effectiveness of nudges in HRC is not a one-size-fits-all proposition, the design and implementation of effective nudges require careful consideration of various factors. One critical aspect is the inclusivity of nudges – ensuring that they are tailored to accommodate the diverse needs, preferences, and abilities of different individuals. Therefore, a critical question that demands further exploration is: how do individuals respond to different nudge delivery methods and techniques?

This research aims to fill this gap in knowledge by conducting a comprehensive investigation into the effectiveness of different delivery methods and techniques in creating inclusive nudges for human-robot collaboration. Through a series of empirical studies involving human participants interacting with robotic systems in controlled laboratory settings, we will systematically manipulate various aspects of nudge design and evaluate their impact on user responses. This research will adopt a mixed-methods approach, combining quantitative analysis of behavioural data with a qualitative examination of user experiences and perceptions. By triangulating findings from multiple sources, a more comprehensive understanding of how individuals respond to different delivery methods and techniques used in creating inclusive nudges for human-robot collaboration can be achieved

Three common forms of nudge delivery methods will be explored, these are visual, audio, and haptic cues. The visual nudges can be displayed through augmented reality overlays that could either be text messages or light signals. The audio delivery method can be delivered through chimes, voice prompts, or simulated variations in the robot's operational sounds. The haptic delivery method involves sending vibrational signals to the user's skin in various frequencies and durations. The optimal delivery method might depend on the specific task at hand, the surrounding environment (noisy workshops might necessitate visual or haptic nudges), and even individual user preferences.

The techniques employed in the nudge itself also warrant investigation. The techniques encompass the specific strategies used to design and deploy nudges effectively. Borrowing from the behaviourist approach by B.F. Skinner [4], which focuses on observable behaviours and how they're shaped by external stimuli through reinforcement, this study will investigate the positive and negative reinforcement techniques. The positive reinforcement nudges will involve highlighting the desirable course of action for the users. Conversely, the negative reinforcement nudges will subtly draw attention to the user after they carry out undesirable actions. By systematically exploring the impact of various delivery methods and techniques on user behaviour and perceptions, we can gain insights into the factors that contribute to the success or failure of inclusive nudges in human-robot collaboration scenarios.

2 LITERATURE REVIEW

This section reviews relevant literature on nudge theory, its application in human-robot collaboration (HRC), and the use of mixed reality (MR) interfaces for delivering nudges. Initially, this research will explore the theoretical underpinnings of nudge theory and its potential benefits within manufacturing settings. Subsequently, it shall examine the role of MR interfaces in delivering nudges and review studies investigating the use of multimodal cues during HRC tasks.

2.1 Nudge Theory

Nudging is a concept that leverages the design of digital interfaces to subtly influence user behaviour popularised by a book by Thaler and Sunstein from [2]. It is based on two principles, choice architecture and libertarian paternalism. Choice architecture is "the environment in which people make decisions" [5], while libertarian paternalism is the need for a nudge to help people make better decisions. A nudge therefore represents a gentle push towards a desirable goal and is designed to influence people to make beneficial decisions for society and/or individuals. The concept originates from economics and political theory for influencing decisions and behaviour using suggestion, positive reinforcement, and other non-coercive means to achieve socially desirable outcomes. In nudge theory, humans are assumed to make irrational choices [6]; this is an intentional depart from the assumption that has undergirded the traditional economic models—homo economics, humans make rational choices through constant comparison among multiple-choice options and optimisation of their choices, they are expected to make irrational choices, according to the nudge theory, and that is why the choice architecture needs to consider their irrationality[5].

Nudging has been applied in several domains. For instance, Harbach et al., [7], redesigned the permissions dialogue of the Google Play Store to nudge people to consider the risks entailed in giving permissions to apps, while Lee et al.,[8] leveraged knowledge about three cognitive biases to design a robot that promotes healthy snacking. Individuals can be 'nudged' to save money and make more substantial contributions to their wealth. Sabbaghi et al [9] also emphasised the effects of nudges that can influence an individual's choice to borrow more responsibly and lead healthier lives while Abouzied and Chen [10] illustrated a technological implementation of the nudge to create a more social environment for users.

In the production and manufacturing sector, assembly tasks, maintenance tasks, and quality control tasks are considered some of the most highlighted tasks in the manufacturing setting due to their fundamental roles in ensuring the efficient production, safety, and consistent quality of manufactured products [11]. These tasks collectively form the backbone of manufacturing operations, where precision, reliability, and attention to detail are of paramount importance. These tasks are enhanced by data-driven insights and therefore, understanding the learning curves of assembly workers, the impact of task structures, and the importance of time management are pivotal facets of this optimisation [12].

Data plays a vital role in optimising assembly and maintenance tasks. Understanding the learning curves of assembly workers and the impact of different task structures is critical [13]. The data collection process, as explored by Pena et al helps identify trends and patterns in performance. One key finding is that breaking down tasks into one step at a time, rather than multiple tasks per step, reduces the error rate. From an information delivery approach, less information per task is considered better, as it simplifies the process and reduces the pressure on the person performing the task. However, this isn't a standalone solution since Villani et al.,[14] showcases the need for more information for novice workers compared to experts. However, as a general framework without considering expert levels, this aligns with the concept that "less is more" when it comes to delivering instructions and information during assembly and maintenance tasks [15]. This helps streamline the information presented to the worker, ensuring that they focus on one task at a time and are not overwhelmed with excessive information.

In assembly and maintenance tasks, augmented reality instructions for time-critical assembly tasks reveals the significance of time management in these processes. Assembly tasks often have strict deadlines and require precision and efficiency. Augmented reality instructions aid in these time-critical scenarios by providing real-time guidance and feedback [16].

2.2 Mixed Reality for HRC

Effective HRC hinges on clear and intuitive communication [17]. Nudge design, with its subtle influence on human behaviour, offers a promising approach. However, the effectiveness of nudges relies not just on the message itself, but also on the delivery method. Previous research has championed visual-based MR interfaces in HRC. A study by Hietanen et al.[18] showcases how AR interfaces, implemented on projectors or head-mounted displays, improve safety and task completion times in engine assembly tasks. Here, visual cues like highlighted trajectories or projected paths subtly guide the human worker, promoting efficient collaboration.

While visual cues offer a clear picture, auditory cues can penetrate noisy industrial environments where visual information might be obscured. Studies have explored the effectiveness of audio cues in HRC. Bolano et al. [17] implemented a system that combined visual feedback with acoustic alerts to inform workers of potential robot collisions. This auditory cue, a timely chime or a change in the robot's operational sound, promotes safety and reduces human anxiety regarding robot movement. Beyond visual and auditory cues, haptic cues offers a unique advantage. Vibrotactile devices worn by human collaborators can provide non-intrusive yet effective communication [19]. A study by Grushko et al. [20] demonstrates the effectiveness of haptic feedback in reducing task completion times and enhancing user satisfaction compared to visual or auditory cues alone.

The true power of nudges in HRC lies in their orchestration. A study by Strazdas et al. [21] highlight the benefits of multimodal interfaces that combine visual, auditory, and haptic cues. This multimodal symphony of nudges creates a clear, informative, and engaging experience for the human collaborator.

3 EXPERIMENT DESIGN

This study presents a structured experimental design aimed at evaluating the impact of real-time visual, audio and haptic cues in the collaborative cube assembly game. The study focuses on the utilisation of positive and negative reinforcement strategies for performance, safety, and well-being notifications through audio, visual, and haptic cues. The goal is to assess how these two reinforcement strategies influence participants' performance, safety compliance, and stress levels while utilizing the three cues.

3.1 Participants and Experimental Conditions

A total of 30 participants with or without prior LEGO assembly experience, will be recruited for the study. Participants will be randomly allocated to one of two experimental conditions: positive nudges or negative nudges. This between-subjects design ensures a clear comparison between reinforcement strategies. All participants will be briefed on the assembly task and familiarised with any necessary equipment, including MR glasses and controllers. Participants in the positive nudges group will receive reinforcement based on successful performance, adherence to safety protocols, and low error rates. This group will use visual, audio, and haptic cues in sequential phases to guide and encourage participants. In contrast, the negative nudges group will receive reinforcement when performance is suboptimal, when safety procedures are not followed, or when errors occur. This group will experience similar cues, but the cues will serve as correction rather than encouragement.

3.2 Experiment Procedure

Participants will be seated at individual workstations equipped with MR glasses and controllers, where they will receive instructions on the assembly task, as well as guidance through the various cues. They are then to complete a series of cube constructions across three phases, each employing a distinct type of cue in a sequential order. In phase 1, participants will receive visual cues based on performance, safety, and well-being criteria. In phase 2, audio cues will be provided to reinforce the same criteria. Phase 3 will utilise haptic cues to continue guiding participants through the task. The triggers will be based on participants' actions during the task and will be activated in response to performance speed, adherence to safety procedures, and error rates. Data will be collected throughout the task, including assembly time, errors, completion rates, and instances of risky behaviour. Pre- and post-task stress levels will also be assessed using standardised questionnaires.

Upon completing the task, participants are to provide feedback on their satisfaction, the perceived effectiveness of the cues, and their overall experience. Stress levels will be measured before and after the task and compared using paired t-tests to evaluate changes within each group. Participants will also assess their overall experience and well-being during the task. Statistical analyses will be conducted to evaluate the impact of experimental conditions on performance, safety, and well-being. Performance metrics will be analysed to examine differences in assembly time, errors, and completion rates between the two groups. Safety outcomes will be assessed using chi-square tests to compare the frequency of safety incidents between groups. Stress level changes will be compared using paired t-tests to evaluate differences in pre- and post-task stress levels within each group. These analyses aim to provide insight into the efficacy of reinforcement strategies on performance, safety, and stress levels, contributing to a broader understanding of human-robot collaboration and task optimisation.

4 DISCUSSION

In conclusion, the ongoing study represents a pivotal exploration of the convergence of digital twin technology, MR interfaces, and the behavioural science of nudging within the manufacturing domain. Central to this investigation is the examination of how individuals respond to various forms of nudges delivered through MR glasses within a digital twin system. The integration of nudging principles within a digital twin framework offers a novel approach to enhancing workplace behaviours and decision-making processes. By leveraging MR glasses as the delivery mechanism for nudges, this study will not only provide a real-time, contextually rich environment but also offer the potential for seamless integration of nudging strategies into everyday manufacturing operations.

As a work-in-progress paper, this study lays the groundwork for further exploration and refinement of nudging strategies within digital twin-enabled manufacturing environments. The insights gained from this research not only contribute to our understanding of human-computer interaction and behavioural economics but also pave the way for future innovations at the intersection of technology, psychology, and organisational science. In doing so, this study underscores the transformative potential of integrating nudging principles within digital twin systems to drive positive behavioural changes and enhance operational performance in manufacturing contexts.

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