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May I Have Your Attention?! Exploring Multitasking in Human-Robot Collaboration

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Abstract:
Human-robot collaboration promises to free the human to multitask and engage in cognitive work while the robots assists with physical tasks, therefore increasing productivity. However, this collaborative paradigm requires continuous attention from human operators, which could potentially strain their cognitive resources. Excessive attention demands can lead to safety hazards, increased errors, and reduced efficiency. Despite its critical importance, there is limited empirical research on attentional factors in industrial human-robot collaboration. In this study, we explore attentional multitasking in collaborative human-robot assembly settings. Our experimental setup involves participants performing a wire harnessing task with a collaborative robot while simultaneously completing a Go/No-Go test as a secondary task. To observe the effect of multitasking, we varied the difficulty of the secondary task across two levels and analysed its impacts on work performance and workload. Our results confirm threaded cognition theory, suggesting that human-robot collaboration could reduce cognitive capacity by depleting attentional resources, leading to higher errors and cycle times during multitasking. This underscores the importance of a detailed understanding of attentional factors in human-robot collaboration. We discuss our findings and their implications, and provide insights into the adjustment and design of human-robot collaboration tasks in the industry.

Keywords: Attention, Human-Robot Interaction, Multitasking, Collaborative Assembly

1. INTRODUCTION

Collaborative robots (cobots) have been designed to work alongside human operators and promise productivity gains and increased flexibility (Sherwani et al., 2020). The integration of cobots in manufacturing and assembly prompted a new line of research on human-robot collaboration (HRC), where humans work together with robots in a shared workspace. Prior works often exemplify the value of HRC as the optimal combination of automation to handle physical tasks while utilising cognitive skills of the human agent (Michalos et al., 2022; Othman and Yang, 2022). In theory, the robot taking over labourious manual tasks should free the human to engage in additional cognitive tasks. Therefore, multitasking in HRC has been proposed to further increase productivity (Chacón et al., 2021). Such applications can include simultaneous HRC and quality control, or working together with multiple cobots at the same time. However, multitasking requires the operator to split their attention among multiple tasks, which can in turn increase the load on the operator and reduce efficiency. Although cognitive load has already been studied in HRC (Carissoli et al., 2023), research on attentional factors is still lacking. Overall, depleting attentional resources through improper design of HRC applications might result in overseeing errors or reduced awareness of safety risks.

In this paper, we investigate the feasibility of attentional multitasking in collaborative human-robot assembly. We performed an exploratory study in which participants carried out a wire harnessing task with a cobot, while simultaneously engaging in parallel attention-demanding task through a Go/No-Go test. To evaluate the effects of multitasking, we designed the Go/No-Go test with two levels of difficulty in terms of their attentional demands. We conducted a user study with 16 participants and gathered quantitative metrics on task performance and response rates and qualitative feedback to evaluate the ability of engaging in secondary attentional tasks. Our experiment suggests that multitasking scenarios may lead to higher cycle times and potentially even increased errors, and operators might be prompted to adapt to the attentional load by prioritising only one of the tasks. Although we

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view multitasking in HRC as feasible, we raise concerns about potential effects on productivity and call for future research on designing HRC applications that don't deplete attentional resources.

2. RESEARCH BACKGROUND

2.1 Multitasking

Multitasking is defined in cognitive psychology as the capacity to manage more than one task at a time. Multitasking can be simultaneous execution of more than a single task (Pashler, 2000), a switching between multiple tasks that execute in parallel (Rogers and Monsell, 1995), or a combination of both in which frequent switching of attention is required. This capacity is essential in industrial environments, as individuals often handle multiple tasks, impacting both their cognitive workload and task performance. Theoretical frameworks, such as multiple resource theory (Wickens, 2008), propose that the effectiveness of multitasking depends on the cognitive resources needed for the activities. There is evidence that separate perceptual modalities follow independent attentional capacities (Alais et al., 2006; Chun et al., 2011; Arrighi et al., 2011), but recent results also suggest tasks requiring central attention based on perceptual input nevertheless share attentional resource; both unimodal and bimodal dual-tasks lead to increased overall load, with equivalent costs following increased task difficulty (Fougnie et al., 2018). The theory of threaded cognition (Salvucci and Taatgen, 2008) goes even further, suggesting that when performing multiple tasks, several mental processes run in parallel, with limitations imposed by resources such as attention and working memory. These theories explain how competing for limited mental resources when performing multiple tasks might make it difficult to focus on each task at a high enough level to ensure good performance (Taatgen et al., 2009; Rohrer and Pashler, 2003; Weigl et al., 2013), with possible detrimental effects leading to errors and accidents (Appelbaum et al., 2008; Metz et al., 2011).

2.2 Attention and Awareness in HRC

The demands of attention and cognitive load are significant factors that impact operators' situational awareness in industrial environments (Umbrico et al., 2023; Nicora et al., 2021). The concept of situational awareness, as defined by Endsley, refers to the "perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1995). In the context of HRC, this translates to an understanding of the cobot's actions, intentions, and the overall state of the manufacturing process by the human operator. Prior research has highlighted the significance of operator awareness for task performance, safety, and productivity in HRC. Liu and Wang conducted a study investigating the impacts of awareness on manufacturing work, demonstrating that enhanced awareness leads more efficient and safer interactions with robots in a manufacturing environment (Liu and Wang, 2021). Additionally, the influence of cognitive fatigue on task performance and situational awareness in HRC was investigated in (Hopko et al., 2021). Their findings suggest that attentional demands have a substantial effect on cognitive fatigue, which in turn affects situational awareness. A study performed in (Paletta et al., 2019) investigated the correlates of visual attention measured by an eye tracker, situational awareness, and performance in HRC. Their results highlight the significance of attentional factors, with visual attention metrics being the main predictor for performance and awareness in HRC. In multitasking scenarios, operators are required to continuously adapt to changing tasks and the robot behavior, hence posing a high load on their attention and awareness. However, it is still unclear how attentional demands impact the error rates and the workload imposed on the operator in multitasking HRC scenarios.

3. EXPERIMENT

This experiment was designed to divide participants' attention, providing a realistic assembly scenario where the participant must balance the attentional load of the main task while also responding to the demands of the secondary task to simulate multitasking. The main task involved working on a wire harnesses in collaboration with a UR5e cobot, while the secondary task involved a Go/No-Go test to impose increased attentional demands. The experimental study was carried out at the Industry 5.0 laboratory at the University of Pannonia (Ruppert et al., 2022).

3.1 Participants

The study included a diverse cohort of 16 participants, consisting of 12 men and 4 women, representing a mix of university students and researchers. The age distribution among participants ranged from 21 to 42 years ($M = 30$, $SD = 6.16$), indicating a diverse demographic profile. All participants gave their consent to take part in the study.

3.2 Design and Procedure

To assess how multitasking affects HRC, we introduced two levels of difficulty for the secondary task while keeping the main task constant. Our study used a within-subjects design, where participants performed two sessions, one for each difficulty level of the secondary task (Figure 1). To mitigate order effects, we counterbalanced the sequence of the sessions for each participant. Moreover, training sessions were introduced before the experiment to further reduce potential order effects. First, the participants were introduced to the secondary task, which required participants to react to changes in screen colour through pressing a pedal on the floor. The frequency of these changes mirrored the conditions of the actual experiment; however, the training task was designed in a different manner than the task encountered in the experiment. Subsequently, the participants were introduced to the main HRC task, which involved wire harnessing in collaboration with a cobot. During this phase of training, participants practiced the wire harnessing procedure and interacting with the cobot. Besides order effects, the purpose of these training sessions was to ensure that participants were comfortable with the tasks, and minimise potential differences in dexterity.

Main task: During the main task, the cobot held a cylindrical hub that served as the central component of

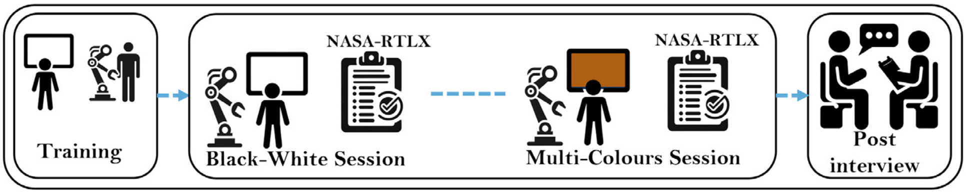


Fig. 1. Overview of the setup and the procedure of the study. The task order was counterbalanced, with 8 participants starting with the black-white condition, and 8 starting with the multi-colour session.

the task. The cobot swiftly rotated the hub to indicate the next assembly step to the operator, assisting in the assembly process. This rotation aligned the terminal block connectors, making it easier for the participant to continue the activity without any interruptions. The assembly included 24 wires with 12 emerging from the rear side and 12 from the front side of the cylindrical hub. These wires were to be connected depending on their label. The label was indicated by a combination of symbols and shapes. The labels simulated part numbers, which are commonly used in industrial assembly to recognize corresponding assembly components. To introduce a challenging aspect to the experiment, the colours of the wires were intentionally varied. The task involved three main steps: (1) Selecting one of the wires extending from the back of the cylindrical hub and attaching it to the terminal block connector using a screwdriver. (2) Identifying the correct counterpart wire based on the symbol and shape combination and attaching it to the terminal block connector using the screwdriver. (3) Verifying the integrity of the connection.

The possible mistakes in the primary task included mismatching of symbols and shapes, unintentional insertion into an adjacent terminal block connector rather than the designated one, insecure wire connections susceptible to detachment, or the total absence of a wire connection.

Secondary task: While the participants were engaged in the main task, a secondary task was introduced to evaluate their attentional capacity. The secondary task was deployed in form of a Go/No-Go test on a screen positioned in front of the participants. To evaluate the influence of attentional multitasking, we designed two conditions with different levels of attentional load.

The first condition was designed as a Go/No-Go test with a lower level of difficulty in terms of attentional demands. The test consisted of a white screen, with a black screen randomly appearing for two seconds within 15-second intervals. The timing of the stimulus was not predetermined and did not follow a regular pattern during the session, making it unpredictable. Hence, participants needed to constantly focus on the attentional test, while also focusing on the human-robot assembly. Each time when the stimulus in form of the black screen was presented, the participant was required to perform a reflexive action by pressing a pedal with their foot. This task assessed participants' ability to sustain attention and respond effectively within the requirements of the main task.

In the second condition, we implemented the same test, but with a higher level of attentional demand, primarily influenced by the increased frequency of stimuli presentation. Three different colours — grey, brown, and white — served as No-Go stimuli, with the Go stimulus again being a black screen. Each of the No-Go colours appeared briefly and randomly for two seconds. Once every 15 seconds, a Go stimulus was presented, with random timing. This experiment required the participants to sustain a higher level of attention on the frequency of the stimuli, as they had to differentiate between Go and No-Go stimuli. The responses were, again, registered via a pedal on the floor.

The possible mistakes in the secondary task included failing to react to the desired colour, or incorrectly responding to a different colour. These possible mistakes were tracked by a code used to build the secondary task. Counterbalancing the conditions was achieved by splitting the participants into two groups, with eight participants starting the experiment with the simpler (black) condition, and eight participants starting with the harder (coloured) condition (Figure 1).

3.3 Data and Analysis

We performed a quantitative analysis on self-reported data collected through post-experiment questionnaire, as well as objective metrics. The objective metrics included task completion time (TCT), the number of errors in the main task, the number of times the participant missed the stimulus in the secondary attentional tasks, and the number of errors in the secondary task. The subjective metrics were collected through the NASA RTLX questionnaire. The analysis was conducted using a two-tailed paired samples t-test. Due to the exploratory nature of our study and the low sample size, we also report descriptive statistics as supplementary metrics.

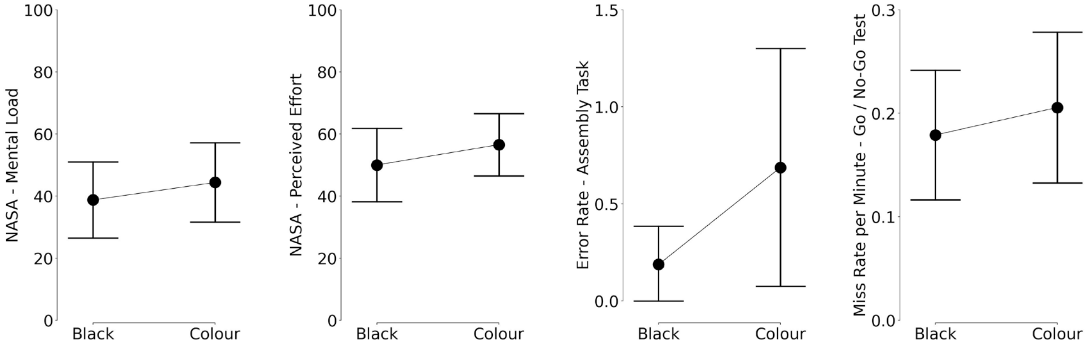
Additionally, we complemented the quantitative results by a qualitative analysis via post-interviews. The participant selection for the interviews was based on a manual data analysis, where we identified seven participants , and asked them further questions with regard to their perception of the differences among the two conditions.

For our study, we assumed that the two conditions will exhibit a difference in mental workload measured by NASA RTLX. We base this hypothesis on the theory of threaded cognition, which suggests that increased attentional demands contribute to higher cognitive load. Additionally, we hypothesised that there will be differences in the objective metrics, while the overall workload will remain statistically equal.

4. RESULTS

4.1 Quantitative Analysis

First, we analysed the differences in the perceived mental load between the two conditions. Student's t-test showed



(a) Mental load (b) Perceived effort (c) Assembly errors (d) Miss rates

Fig. 2. Comparative plots of the mean and the confidence intervals ($CI = .95$) for the two conditions and per variable.

a weakly significant effect with $t(15) = -2.087$, $p = .054$, and Cohen's d of -0.522. Our analysis also revealed a weakly significant difference in perceived effort between the two conditions ($t(15) = -1.787$, $p = .094$, Cohen's d $= -0.447$). The descriptive plots of the two variables are depicted in Figures 2a and 2b. This indicates that the colour condition was perceived as cognitively harder, with a small to medium effect size. No other subjective metrics from the NASA RTLX questionnaire showed a significant difference. This correlates with our expectation, as we controlled for an increased attentional load, while the overall workload for the task remained the same.

Regarding the performance metrics, assembly errors were analysed using the Wilcoxon signed-rank test (Shapiro-Wilk test, $p - value < .05$), which yielded no significant differences ($Z = -1.618$, $p = .134$). Although not significant, as the majority of the participants did not perform any errors in the assembly task, the descriptive statistics (Figure 2c) indicate a possible trend towards more errors during the secondary task in the colour condition. To analyse the performance of the secondary tasks, we investigated the miss rate, i.e., the number of time the participant did not react to the Go-stimulus. As the number of stimuli in the experiment was dependent on the task duration, we scaled the variable by the experiment duration to ensure comparability. The test did not reveal any significant differences ($t(15) = -1.117$, $p = .282$). The descriptive results of both errors rates are depicted in Figures 2c and 2d.

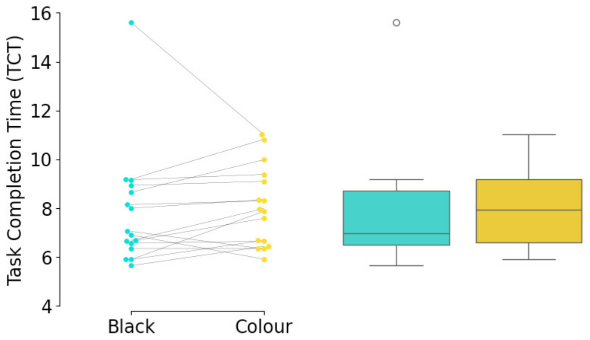


Fig. 3. Swarmplot and boxplot of the differences in task duration per condition.

Finally, we have analysed the effect of the two conditions on the task completion time (TCT). As the black condition contained a strong outlier and the Shapiro-Wilk test yielded a $p - value < .05$, we again deployed the Wilcoxon signed-rank test to analyse the data. The results displayed a Z-score of -1.647 ($p = .105$). Despite non-significant results, the effect size of -0.483 (rank-biserial correlation) and the descriptives provided in Figure 3 indicate a trend towards more time needed for the colour condition.

4.2 Qualitative Analysis

One week after the experiment, we invited selected participants for a post-interview. This included random participants, selection based on observation during the experiment, or participants whose data contradicted the trend, such as in the case of the participant with a very long task duration in the black condition (Figure 3). We analysed the statements from the participants, and clustered the data into three themes:

- *Strategy Adaptation* - the split of the attention forced some participants to reduce their focus on one task and prioritise the other to avoid mistakes. This was, for example, the explanation for the outlier TCT in Figure 3. In this case, the participant was overly focused on the secondary task not to miss the stimuli, which lead to a high completion time of the main task.
- *Learning Effect* - three participants mentioned that they got more comfortable with the experiment over the time, and thus they made less mistakes and also perceived the second session as easier, disregarding whether they experienced the black or colour condition in their second experiment.
- *Subjectivity and Fatigue* - some participants perceived one of the conditions easier, despite making more mistakes than in the condition they perceived as harder. Moreover, two participants gave different statements with regard to their perception of the two conditions, with the responses from the interview contradicted their NASA metrics. Through further questions, they attributed this to fatigue.

5. DISCUSSION

Prior works on HRC in manufacturing often assume that humans can effortlessly transition to cognitive tasks while robots assist them with labourious manual tasks. However, engaging in collaboration with a robot requires attention, which can deplete attentional resources required for other tasks. We studied how attentional multitasking in HRC impacts productivity and explored the potential disadvantages. Although not statistically significant due to the exploratory nature of our study and low sample size, our results indicate that workers are required to split their attention to manage multiple tasks. This can potentially reduce productivity, as evidenced by a trend towards more errors in assembly tasks. Additionally, while the miss rate in secondary tasks did not show significant differences, the descriptive results suggest that attentional multitasking could transition into workers overseeing quality-related issues and their awareness of the environment and work can be reduced. In turn, this can pose safety related issues. Moreover, we observed potential implications for task completion time, with a trend towards increased duration in conditions where the secondary task poses increased cognitive demands. These findings underscore the importance of considering the impacts of attentional requirements in HRC to optimize task performance and efficiency.

Our results also show that, when multitasking in HRC settings, participants may adapt their strategy and prioritise one task over another, leading to more errors in the respective task. We speculate that this can be either due to the inability to split attention between multiple tasks, or simply because of the preference to maximising the efficiency in one task while sacrificing efficiency in another. Preferred strategy for multitasking tends to converge towards that of minimal interference to either task, but the process of finding the optimal solution is not automatic, and is not always observed across all participants (Nijboer et al., 2013). Participants' preferred strategy itself may have impact on performance and effort, regardless of task prioritization instructions (Jansen et al., 2016).

The results of our experiments are aligned with the threaded cognition theory, which suggests that cognitive capacity might be reduced due to HRC depleting their attentional resources. It is important to consider real-life examples of such attentional multitasking such as concurrent HRC and quality control, supervision of and collaboration with multiple robots, or being able to flexibly react to short-term interruptions or a problem in the process. Instead of dichotomously adding up the physical capabilities of the robot with the cognitive skills of the operator, we propose to view humans collaborating with robots as a blend of cognitive constraints that are affected by the physical actions of the robot. We aim to challenge the notion of clear-cut boundaries between the agents, and call for a reevaluation of claims related to HRC and productivity gains. Designing HRC applications requires a more nuanced understanding of how attentional and cognitive resources are used, yet, empirical research on such applications in manufacturing is missing.

Finally, we give two design implications based on our experimental study. First, we believe that the integration of collaborative robots should not lead to the exploiting of the limits of cognitive resources by placing additional tasks on workers. Our study indicates that potential consequences might include increased cognitive load and perceived effort, as well as reduced productivity. Still, multitasking can be feasible in opportune moments, such as at times when the engagement in the HRC task is reduced. Transferring this into HRC applications requires an improved communication of robot's intent to the human, indicating when the human agent can reduce their awareness of the robot movement and focus their attention on other tasks. Alternatively, multitasking in HRC could be supported by attention management systems, which have been shown to limit attention fragmentation (Anderson et al., 2018). Second, we advise against the design of HRC applications with parallel, simultaneous multitasking, and propose the sequential approach instead. This involves a clearer definition of task boundaries, for instance, by task allocation and scheduling algorithms, mitigating the risk of having to prioritise one task over the other.

5.1 Limitations and Future Work

The primary constraint in this experiment was the limited sample size due to the exploratory nature of the study. Given the relatively low effect size, there is need to adequately test the generalizability of our results. As such, we intend to reevaluate our findings with a larger sample size study. Our results also indicate the presence of a possible floor effect. This suggests our main task may not have been sufficiently difficult to fully evaluate the whole spectrum of multitasking abilities. Performance effects from multitasking are more apparent when the main task is deemed difficult by the participants (Adler and Benbunan-Fich, 2015). As such, we aim to further tune main task difficulty and study design to better emulate multitasking in real-life manufacturing conditions.

Furthermore, based on our results, we believe that there might be evidence for an interaction between task completion time and errors, both in the main and secondary task. This might provide additional insights into how performance metrics are interrelated in multitasking scenarios. However, our study design did not allow us to perform this investigation. For example, manipulation of stimulus onset asynchrony and task order in dual-tasks have been reported to affect response times, while having no effect on error rates (Kamienkowski and Sigman, 2008). It should be noted however that a common criticism of dual-task design lies in the difficulty of replication due to specificity and customized nature of instruction and task design; parameters such as the choice of modality in each task can influence observed cognitive load, leading to different findings between studies investigating similar qualities (Esmaeili Bijarsari, 2021). To ensure replicability of our results, clear definition of both tasks' modalities as well as correct definitions of assumptions on measurement of cognitive load is important. Additionally, future studies should compare these multitasking scenarios with non-multitasking conditions to isolate the specific contributions of concurrent task management to cognitive load.

6. CONCLUSION

In this work we explored attentional factors in industrial HRC. Through our experimental design, we observed the impact of attentional multitasking with two different levels of difficulty on productivity. We show that secondary tasks with increased attentional requirements may result in productivity decrease in the form of higher error rates and task duration. Our findings underscore the importance of considering attentional demands in the design and implementation of collaborative human-robot applications in manufacturing. Moving forward, our exploratory study aimed to address a gap in empirical research on human factors in HRC. We state our design recommendations for developing applications in order to mitigate potential productivity decrease and prevent increased cognitive demands from workers. We call for more empirical research on industrial HRC to further investigate this interesting field wand shape applications that benefit workers.

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