# The Impact of Motion Scaling and Haptic Guidance on Operators' Workload and Performance in Teleoperation


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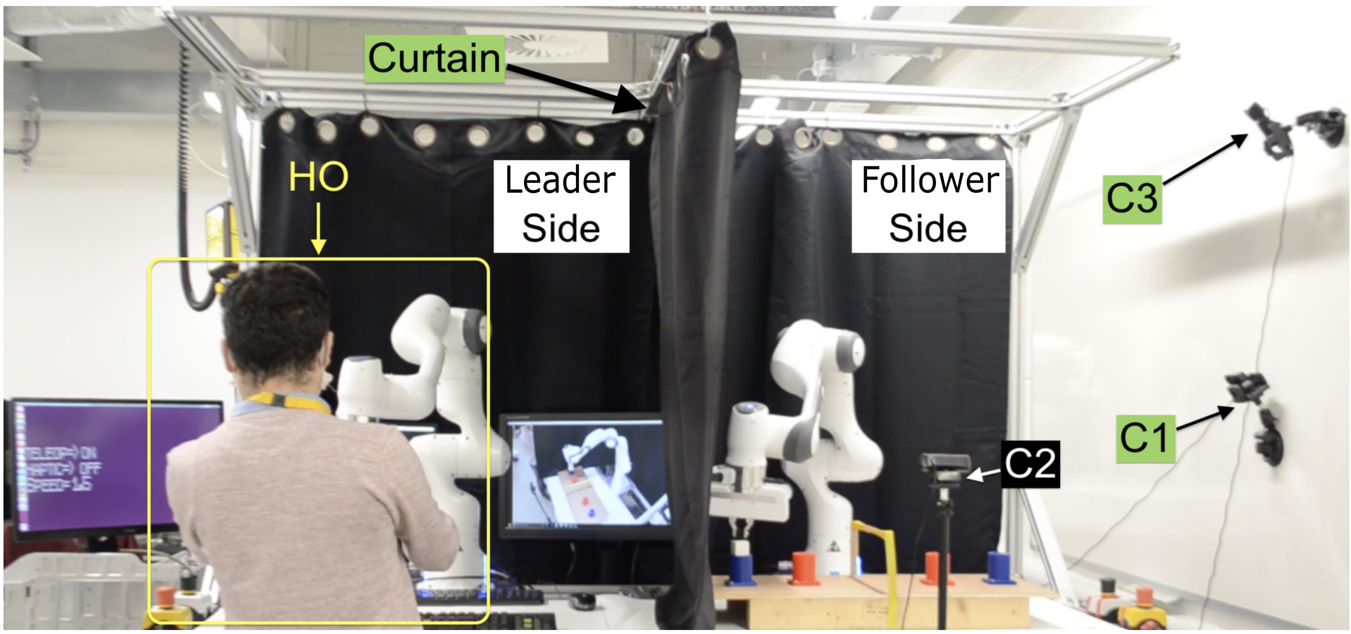


**Figure 1: Teleoperation setup used in this paper. The operator (HO) uses a leader arm to steer a remote device, e.g. a manipulator called follower arm, via looking at the remote workspace through camera views, placed in front of the operator using digital screens. Our setup provides the operator with various operation modes (Haptic On/Off, Motion Scaling 0.5/1.0/1.5).**


## ABSTRACT

The use of human operator managed robotics, especially for safety critical work, includes a shift from physically demanding to mentally challenging work, and new techniques for Human-Robot Interaction are being developed to make teleoperation easier and more accurate. This study evaluates the impact of combining two teleoperation support features (i) scaling the velocity mapping of leader-follower arms (motion scaling), and (ii) haptic-feedback guided shared control (haptic guidance). We used purposely difficult peg-in-the-hole tasks requiring high precision insertion and manipulation, and obstacle avoidance, and evaluated the impact of using individual and combined support features on a) task performance and b) operator workload. As expected, long distance tasks led to higher mental workload and lower performance than short distance tasks. Our results showed that motion scaling and haptic guidance impact workload and improve performance during more difficult tasks, and we discussed this in contrast to participants preference for using different teleoperation features.





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## CCS CONCEPTS

• **Computer systems organization** → **Embedded systems**; *Redundancy*; Robotics; • **Networks** → Network reliability.

## KEYWORDS

Teleoperation, Mental Workload, Usability Testing, Motion Scaling, Haptic-guided shared control

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## 1 INTRODUCTION

Reliability and safety are two main barriers to the use of autonomous robots in industries such as medical robotics [13] or hazardous waste management [14]. Most often, a robotic manipulator is teleoperated in a remote workspace to achieve tasks in extreme conditions. Instances of such conditions include (1) workspaces that are too dangerous for a human operator to enter, e.g. nuclear waste decommissioning [23], (2) workspaces that are too small/invasive for a human to operate in, as per micro/minimally-invasive surgery [20], or (3) the load to be manipulated can be too heavy for the human operator to cope (e.g. demolition tasks [4]). However, conservative industries require a human operator to fully or partially control the robot movements in safety-critical, high-consequence environments (e.g. nuclear [23] or medical [20]) robotics. Whilst these no longer rely on operators' physical force, the human role has shifted towards a control, supervisory, and decision making one for such intelligent teleoperating systems [22].

Fully teleoperating a robotic arm with many degrees-of-freedom (DOF) in a remote workspace (follower arm) via a leader input device, which may be, e.g., a leader-arm, shown in Fig. 1 is complex and imposes high cognitive processes on the operator. However, human operators have a limited capacity [22], that means they can only perform or attend to a limited set of tasks at any one time. When teleoperating in safety critical scenarios, it is necessary that the tools used consider both operators performance and mental workload. It is critical that the operator has the spare capacity to react in case of the unexpected, and prevent Mental Workload Overload [22]. Previous work has already shown the importance of teleoperation support features such as motion-scaling [3, 19], haptic guidance [5, 12, 15, 16], grasping control [8], which each have the potential to support operators during high workload tasks. However, it is not clear how combining control features (such as haptic guidance and motion scaling) impact operators' workload, and how operators can best benefit from such features.

We designed an experiment (N=18) that evaluated the impact on workload and performance of two features integrated with teleoperation (i) scaling the velocity mapping of leader-folower arms (Motion Scaling), and (ii) haptic-feedback guided shared control (Haptic Guidance). We tested these using a purposely difficult peg-in-the-hole task requiring high precision insertion, obstacle avoidance, and short vs long distance travel post grasping.

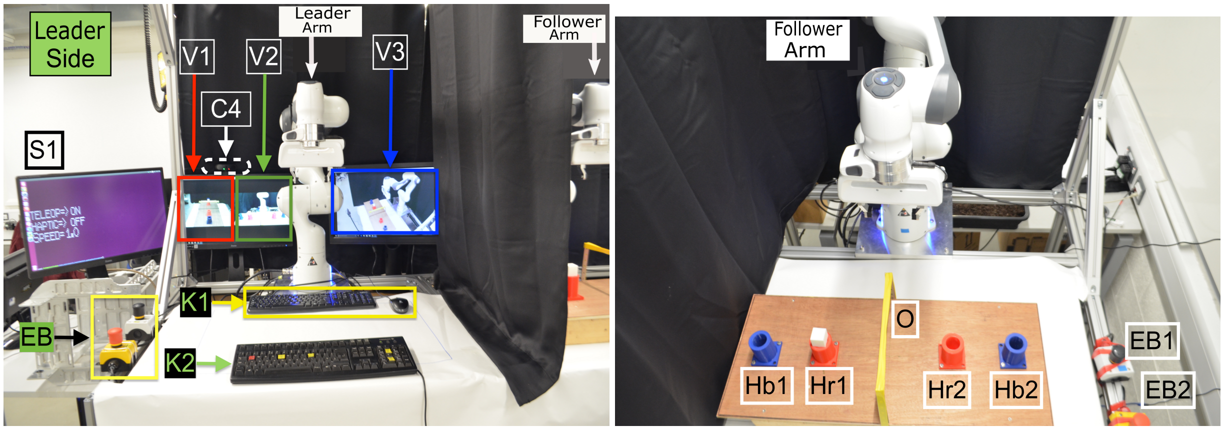
*(i) Motion Scaling.* Motion scaling refers to the ability to control and easily switch the scales of velocity mapping between the leader arm and the follower arm (upscaling e.g. 1:2 or downscaling e.g 1:0.5 the leader:follower movements). Motion scaling has been successfully deployed in teleoperation systems to improve performance and reduce error rates. Richter et al. used motion scaling to enhance surgical teleoperation performance with high delay [19]. Self-adaptive motion scaling has been used in a remote control surgical robotic and was tested on the da Vinci Research kit to improve performance [24]. Different approaches and methods have been proposed and developed, however, and the usefulness and application of motion scaling still requires testing [3, 17] as there is little guidance available on the interaction design of such intelligent features; the questions range from how should the operators interact and change the scale, what is the suitable scale for various teleoperation tasks, how many times will operators change and interact with the scale feature, but also how all this will impact operators' workload. This study replicates prior work investigating the impact of motion scaling on task performance and operators workload during high precision tasks, and we will further extend the knowledge in the field by also considering motion scaling in the presence of haptic guidance.

*(ii) Haptic Guidance.* Haptic devices are small and lightweight robotic manipulators placed on the leader side of a teleoperation system that can apply force and torques on the operators' hands during teleoperation tasks. Haptic devices have the ability to generate Haptic Force Cues (HFC) to provide feedback proportional to the forces/torques sensed by a sensor mounted on the follower arm [11, 20], and inform human operators of constraints in the remote workspace, e.g. collision [15], joint limits [10, 21], singularities [5, 20] and others [1, 2, 18]. Research has shown that non-conventional HFC approaches can significantly improve the teleoperation experience, improve performance, and reduce error rates [12, 16]. This study further evaluates the impact HFC can have on operator mental workload.

In this paper, we discuss our early results focused on overall task performance data, subjective workload using the NASA-TLX questionnaire [6, 7], and a short end survey focused on capturing operators' preference for the teleoperation features.

## 2 EXPERIMENT DESIGN

We built a teleoperation setup consisting of 2 Panda arms manufactured by Franka Emika (as presented in Fig. 1). Panda-1 is a leader arm (Figure 2a) and Panda-2 is a follower arm (Figure 2b). As operators' workload and performance is heavily impacted by the operator workload state, we aimed to investigate two teleoperation support features (Motion Scaling and Haptic Guidance) in both normal and more difficult task scenarios. Hence, we have used a purposely difficult peg-in-the-hole task with obstacle avoidance (see Figure 2b). In this setup, participants used the leader arm to control the follower arm to reach, grasp, and move a peg from one of the holes on the left side of the work table to the same color hole on the right side of the work table. We devised two variations of the task: **(SD) Short Distance** peg-in-the-hole task with 30cm distance between the peg and the target hole (red holes in Fig. 2b), and **(LD) Long Distance** peg-in-the-hole task with 60cm distance between the peg and the target hole (blue holes in Fig. 2b).




(a) (b)

**Figure 2: Teleoperation setup: (a) Leader side including 3 screens. Screen 1 (S1) displays the operation mode, Screen 2 displays the side view of the leader arm (V1) and the front view of the leader arm (V2) and Screen 3 displays the isometric view (V3) of the follower workspace. Leader arm is located in front of the screens. Camera (C4) record the the gesture and gaze of human operators. Keyboard and mouse (K1) is used only for setting up the experiments and keyboard 2 (K2) is used by the operators to switch among different operational conditions; (b) Follower side looking at the remote workspace including 4 holes (namely Hb1, Hr1, Hb2, and Hr2), an obstacles (O) and emergency button (EB).**

## 2.1 Study Conditions

We devised four study conditions to investigate the impact of the motion scaling and haptic-guidance on the operators’ task performance and workload. All participants performed both LD and SD tasks in all 4 study conditions, where both the study conditions and task type were counterbalanced using Latin-square design.

- C1 Haptic-Guidance (On) Motion Scaling (On)
- C2 Haptic-Guidance (On) Motion Scaling (Off)
- C3 Haptic-Guidance (Off) Motion Scaling (On)
- C4 Haptic-Guidance (Off) Motion Scaling (Off)

## 2.2 Collected Data

We collected various types of data during the study. For this initial report, we focus on: Performance (Task Completion Rate and Time to Complete), and Subjective Workload (NASA-TLX questionnaire).

**Task Completion Rate and Time to Complete.** We recorded the number of times participants failed in various task conditions (dropped the peg outside of the hole, miss-grasped the peg, moved the robot outside of the allocated boundary, or run out of time), and time to complete was measured for each of the successful attempts (there was a time limit of 5 minutes for each trial).

**NASA-TLX questionnaire.** We used the NASA-TLX questionnaire, a subjective workload assessment tool [6, 7], based on the weighted average ratings of six sub-scales including (in order): Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration. Each participant was asked to self report their mental workload using the NASA-TLX once after each condition. We additionally investigated each of the sub-scales independently.

## 2.3 Study hypothesis

Our hypotheses sought to investigate operators’ performance, subjective experience, mental workload and preferences.

- H1 Motion scaling will impact operator experience, performance and workload.
- H2 Haptic guidance will impact operators’ experience, performance and workload.
- H3 Haptic guidance and motion scaling will be more useful for difficult tasks (LD) than for less difficult tasks (SD).
- H4 Combining haptic guidance and motion scaling will result in better task performance and operator experience.

## 2.4 Participants and Procedure

18 participants (14 male, 4 female) with an average age of 25.5 years were recruited to take part in the study. The data collection took place during the COVID19 lockdown. In order to minimise the risk of cross infection, we only invited participants that were either university staff or students based in the School of Computer Science, hence the sample was not diverse (everyone had a technical background). Participants had different levels of experience with the teleoperation equipment. The study was approved by the university ethics committee.

As participants arrived at in the laboratory they have scanned a QR code checking into the University Track and Trace system. Participants were equipped with a mask, a pair of gloves, and were invited to read the information sheet and provide consent. We provided an overall description of the two types of tasks, SD and LD and presented the teleoperation equipment. Participants then had the chance to test this during a practice session (up to 10 min). They also had the chance to test the features investigated in this study and they performed multiple peg in the hole tasks. We then invited participants to perform 4 task conditions (C1-C4) * 2 types of tasks (LD and SD). Participants filled a NASA-TLX questionnaire after completing each of the 8 trials. At the end of the study, participants filled a final questionnaire.

# 3 RESULTS

We used repeated measures within subjects ANOVA to compare differences between the 4 study conditions in the two types of tasks, SD respectively LD tasks.

## 3.1 Performance Data

*Time to Complete.* As only 6 out of 18 participants were successful in completing all study conditions, ANOVA only considered these 6 in the analysis, and we were not able to find any statistical significance in the time-to-complete data.

*Task Completion Rate.* A one-way repeated measures ANOVA was conducted to determine whether there were statistically significant differences between the study conditions in the Task Completion Rate. The assumption of sphericity was violated, as assessed by Mauchly's test of sphericity, $p = .001$. Therefore, a Greenhouse-Geisser correction was applied ($\epsilon = 0.798$). We found statistically significant differences between conditions F(4.11, 69.87) = 3.713, $p < .01, \eta^2 = 0.179$, for LD tasks ($C1M = .83, C2M = .56, C3M = .72, C4M = .56$) and SD tasks ($C1M = .89, C2M = .83, C3M = .94, C4M = .94$). Post hoc analysis with an LSD corrections revealed a few differences. When comparing between conditions for the LD tasks participants had a higher completion rate in C1 compared to C2 ($M = .278, 95\%CI[.049, .507], p < .02$). and in C1 compared to C4 ($M = .278, 95\%CI[.049, .507], p < .02$). These results suggest that for using motion scaling, with or without haptic guidance, participants completion rate significantly improved.

We also found differences between the SD and LD task conditions. Participants' performance during SD tasks resulted in significantly higher completion rate. C3 for SD task had significantly higher task completion rate than C3 in for LD task ($M = .222, 95\%CI[.009, .435], p < .04$). The same effect was measured when comparing C4 for both tasks ($M = .389, 95\%CI[.139, .638], p < .004$). In line with what we expected, LD tasks are more difficult in nature, and performing SD tasks results in higher task completion rates.

## 3.2 Subjective Data (S)

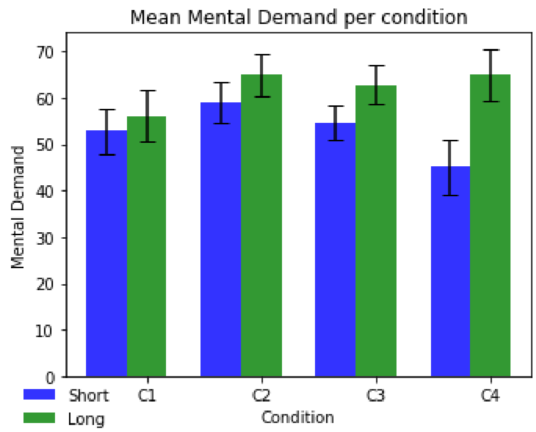
We performed individual analysis on the 6 NASA-TLX sub-scales [6, 7] (see Figure 3). There was no statistically significant differences in the effort and physical demand scales.

*3.2.1 NASA-TLX Mental Demand (S).* A one-way repeated measures ANOVA was conducted to determine whether there were statistically significant differences between the study conditions in the Mental Demand NASA-TLX data (see Figure 3a). The assumption of sphericity was violated, as assessed by Mauchly's test of sphericity, $X^2 = 56.402, p = .001$, and a Greenhouse-Geisser correction was applied ($\epsilon = 0.568$). We found statistically significant differences between conditions F(3.974, 67.566) = 3.883, $p < .01, \eta^2 = 0.186$, for LD tasks ($C1M = 56.111, SD = 24.528, C2M = 65, SD = 20.073, C3M = 62.778, SD = 18.409, C4M = 65, SD = 24.071$) and for SD tasks ($C1M = 52.778, SD = 21.367, C2M = 58.889, SD = 19.063, C3M = 54.444SD = 16.169, C4M = 45, SD = 25.495$). Post hoc analysis with an LSD corrections revealed that participants felt more mentally demanded in C2 compared to C1 for the LD task ($M = -8.889, 95\%CI[-16.496, -1.282], p < .025$). This suggests that during the haptic guidance conditions, motion scaling significantly reduced participants mental demand. We also found that LD tasks generate more mental demand compared to SD tasks ($C4$ in LD $M = 20, 95\%CI[8.815, 31.185], p < .002$).

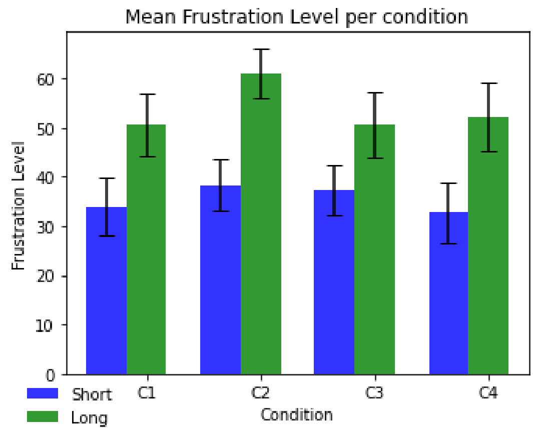
*3.2.2 NASA-TLX Temporal Demand (S).* A similar analysis was performed for the Temporal Demand NASA-TLX data (see Figure 3d). The assumption of sphericity was violated, as assessed by Mauchly's test of sphericity, $X^2 = 44.055, p = .024$, therefore a Greenhouse-Geisser correction was applied ($\epsilon = 0.541$). We found statistically significant differences between conditions F(3.786, 64.386) = 3.269, $p < .01, \eta^2 = 0.161$, for both, LD tasks ($C1M = 52.222, SD = 24.388, C2M = 50.556, SD = 24.608, C3M = 51.667, SD = 24.314, C4M = 55.556, SD = 23.570$), and SD tasks ($C1M = 45, SD = 26.401, C2M = 42.222, SD = 25.101, C3M = 49.444SD = 22.874, C4M = 32.222, SD = 25.566$). Post hoc analysis with LSD corrections revealed that participants felt significantly more rushed and reported higher temporal demands in C1 compared to C4 for the SD task ($M = 12.778, 95\%CI[0.383, 25.173], p < .044$). Participants also felt more temporal demands in C2 compared to C4 for the SD task ($M = 10, 95\%CI[1.137, 18.863], p < .029$), and more temporal demands in C3 compared to C4, for the SD task ($M = 17.222, 95\%CI[-4.332, 29.734], p < .01$). We found that motion scaling, haptic guidance or both of these features during SD (easier) tasks generated more temporal demand, and participants feel more rushed when completing the tasks. When comparing LD task with SD task conditions, we found that generally LD tasks generated more temporal demands (C4 in LD $M = 23.333, 95\%CI[11.640, 35.027], p < .001$).

*3.2.3 NASA-TLX Performance (S).* We repeated the analysis approach for the Perceived Performance NASA-TLX data (see Figure 3c). The assumption of sphericity was violated, as assessed by Mauchly's test of sphericity, $X^2 = 44.332, p = .023$, therefore a Greenhouse-Geisser correction was applied ($\epsilon = 0.569$). We found statistically significant differences between conditions F(3.986, 67.754) = 4.126, $p < .005, \eta^2 = 0.195$, for both LD ($C1M = 25, SD = 25.495, C2M = 42.778, SD = 32.685, C3M = 34.444, SD = 35.184, C4M = 42.778, SD = 33.747$) and SD tasks ($C1M = 16.111, SD = 24.287, C2M = 23.333, SD = 29.635, C3M = 14.444SD = 14.642, C4M = 16.667, SD = 19.097$). Post hoc analysis with an LSD corrections revealed that participants felt they had performed better in C2 compared to C1 for the LD task ($M = 17.778, 95\%CI[1.636, 33.919], p < .033$). When comparing long with SD tasks, we found that generally people perceived to have performed better in the SD tasks (C4 in LD $M = 26.111, 95\%CI[6.504, 45.718], p < .012$, C3 in LD $M = 20, 95\%CI[1.709, 38.291], p < .034$).

*3.2.4 NASA-TLX Frustration.* Frustration NASA-TLX data (see Figure 3b) has also been analysed following the approach above. The assumption of sphericity was violated, as assessed by Mauchly's test of sphericity. The test failed to return any




**(a)**

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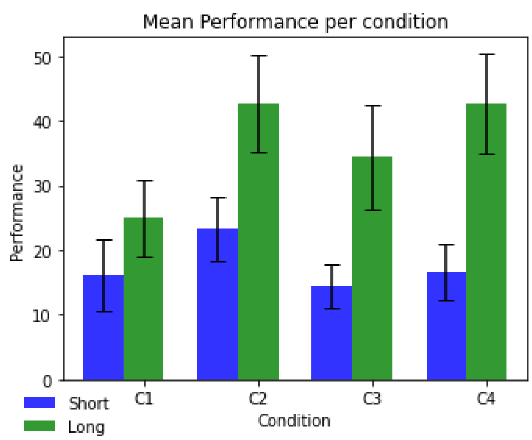


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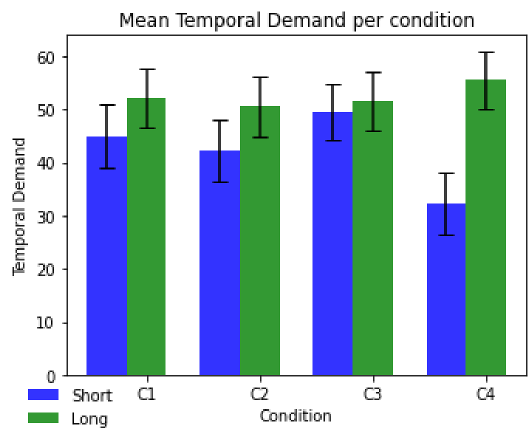



**(d)**

**Figure 3: NASA-TLX results for Mental Demand, Frustration, Perceived Performance and Temporal Demand. Our results show significant differences between various task conditions.**

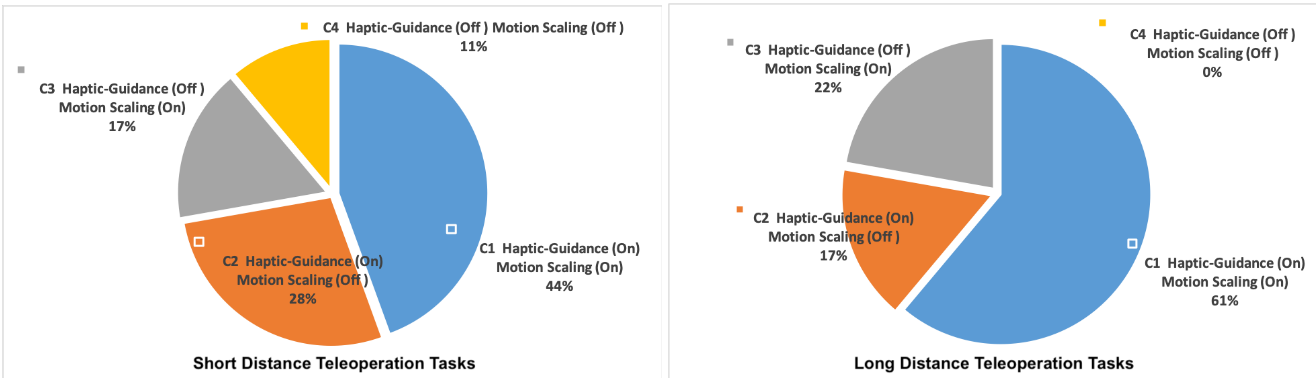
values, therefore, a Greenhouse-Geisser correction was applied ($\epsilon = 0.551$). We found no statistically significant differences between conditions of the same task (long or SD tasks). However, when comparing between short and LD tasks, post hoc analysis with an LSD corrections revealed that participants felt significantly more frustration levels during the LD (more difficult) task scenarios (C1 $M = 16.667, 95\%CI[2.498, 30.835], p < .025$, C2 $M = 22.778, 95\%CI[8.124, 37.431], p < .005$, C4 $M = 19.444, 95\%CI[3.492, 35.397], p < .025$).

## 4 DISCUSSIONS

In this paper we presented and evaluated two teleoperation features, motion scaling control and haptic guidance shared control during two types of teleoperation tasks (SD and more difficult LD peg-in-the-hole).

Features such as Motion Scaling have been previously shown to support operators during teleoperation tasks [17, 19]. We hypothesised (H1) that motion scaling will impact participants performance during tasks. In line with previous findings [17, 19] our results showed that that motion scaling significantly improved the performance for the long distance (more difficult) tasks. This was the case for both when haptic-guidance was On and Off. Moreover, for difficult task scenarios participants were more likely to fail if they had no motion scaling.

We have also expected that participants' workload will also be impacted. Interacting with an additional operating feature (H1, motion scaling) may require more attentional resources, therefore impacting the demands which may results in higher workload. Our results however showed that during haptic guidance conditions, motion scaling in fact significantly reduced participants mental demand. Our results also revealed that using motion scaling (H1), haptic guidance (H2) or both of them during short distance (easier) tasks yields more temporal demand, and participants feel more rushed. This suggests that perhaps the individual (H1, H2) or the combined features (H4) could be more useful during more difficult task scenarios (H3).




(a) (b)

**Figure 4: Participants preference for using the teleoperation support features during the short and long distance tasks.**

In contrast to the performance results (task completion rate), participants felt they have performed better (as indicated in the NASA-TLX Performance scale) with the haptic guidance whilst performing the more difficult tasks (H3). This is in line with previous work [12], which suggests that shared control in haptic systems can have a positive impact on performance.

In line with our expectations (H3), while we found significant differences between conditions for the short distance tasks, most of our findings revealed differences in conditions for the long distance task scenarios. As these tasks required more effort, the use of the support teleoperation features made a difference, resulting in a significantly better overall performance. These findings also suggest the importance of testing advancements in teleoperation systems with tasks that vary in complexity in order to fully understand the impact they create on task performance, workload as well as operator experience. Previous work has already showed how various teleoperation support features can significantly improve the teleoperation experience, performance and reduce error rates [17, 19]. In this study we have also tried to understand the impact of combining multiple teleoperation features simultaneously (H4), namely haptic guidance and motion scaling. Our results generally found that combining the two features improves the task performance, especially for the long distance (more difficult) task scenarios. We found no evidence that there is an impact on workload.

Participants opinions also indicated a preference for using the proposed teleoperation features as seen in Fig. 4. In most cases participants preferred the combined motion scaling and haptic guidance (H4), and, in long distance tasks participants always preferred at least one of the two features. Most of participants had positive comments anout the teleoperation spport features (P201 - "I found the haptic guidance helpful and quick... it could increase the speed when moving the pin ...", P213 refering to LD tasks ... *haptic helps as it reduces the physical workload*, P215 - *using motion scaling makes it "... easier to navigate the robot over larger distances ... turning the scale up made the robot easier to move over the long distance... I could turn the scale down for more precise movements"*). Some participants also indicated having different opinions for the motion scaling and haptic guidance in specific SD as compared to LD task conditions (P208 - *"Haptic (guidance) took away some autonomy doing the task. While scale was a tool I could use, haptic felt like it was using me. Scale was especially useful for the longer distance."*, P209 - *"Haptic was minimally helpful but still covered some distance for me. Scale made moving over the obstacle faster and easier."*, P213 - *"the haptic felt unnecessary in the short distance (tasks)"*). Participants identified and reported when certain features were more helpful during the teleoperation tasks. Haptic guidance (H2) was *"vital in reaching the pick-up goal initially"* (P212), and *"useful when handling objects carefully at low speeds ... and when positioning the cube into the hole"* (P217). Scale was useful (H1,H3) *"after picking up the object and haptic can guide you to pick up the object"* (P205) and *"... with a larger distance the scale helped move the arm with less physical effort* (P213).

## 5 CONCLUSION

Interfaces and systems used for critical tasks (such as teleoperation) must allow operators the spare capacity to react in case of the unexpected [9, 22]. We integrated and combined two useful features integrated with the teleoperation (i) motion scaling, and (ii) haptic-guided shared control in a symmetric tele-manipulation system. We evaluated the usefulness of these features and their impact on operators' performance and mental workload during tasks that varied in complexity (SD and LD). We found that the scale control and haptic guidance impact workload and significantly improve performance during more difficult task scenarios. We discussed the implications of using these features in different contexts, and we contributed to the development and evaluation of autonomous robotics systems.

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**Data Access Statement.** A dataset is available that contains: NASA TLX subjective ratings, demographics and end questionnaire, in CSV format.

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