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Factors Influencing Operator Expertise in Bilateral Telerobotic Operations: A User Study

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Abstract— **This paper presents a detailed user study aimed at experimentally comparing the experience levels within bilateral teleoperation. The primary objective is to elucidate the key performance metrics that can effectively evaluate the competency level of human operators. Existing methodologies typically focus on the quantitative psychological evaluation of human-in-the-loop systems rather than operator performance. In our experimental study, six novice and four professional operators participated in various telerobotic activities. Various parameters, including task completion duration, errors, remote manipulators' motion, and subjects' gaze information, were captured. Subsequently, the measured performance parameters across all subjects were compared with respect to their level of proficiency through statistical analyses. The results indicate that tasks were performed more quickly by experienced operators, fewer mistakes were made, and remote manipulators were operated more smoothly (e.g., fewer jerks and better maintenance within the centre of the workspace). Additionally, better compensation for the lack of depth perception was demonstrated by experienced operators through effective scanning of multiple viewpoints.**

I. Introduction

Telerobotic systems empower humans to manipulate objects from a distance, and bilateral systems further enable operators to execute delicate and dexterous tasks remotely and safely. As a result, significant research efforts have been directed towards enhancing the performance of these systems, which have become integral operational components across various industries, including nuclear, subsea exploration, military, and robotic surgery [1], [2]. Evaluating the performance of such systems involves measuring both quantitative and qualitative performance metrics, where later one includes uses studies given their human-in-the-loop nature [3]. Additionally, in safety-critical systems, operators undergo extensive training programs to attain proficiency (e.g., can take up to 2 years to be a fully experienced remote handling operator for the Joint European Torus) [4]. However, it remains unclear what defines an expert operator and which qualitative metrics should be used to benchmark the performance of such systems.

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Over the past two decades, studies on Human-Machine Interfaces (HMI) have predominantly focused on interface devices like computer mice, keyboards, and joysticks. In the absence of advanced embedded vision technologies like gaze tracking systems [5], researchers have conducted studies to capture user/operator attention on 2D screens by tracking mouse or joystick movements. These studies assess metrics such as the number of mouse clicks in specific areas and task/game completion times [6]. For instance, usability studies evaluating display designs (e.g., websites, games, HMIs) measure properties like travel time between buttons, average time to locate the correct button, time to traverse, percentage of undo/reverse actions after clicking on a button, and more. These metrics serve as indicators of the usability of the design, especially for untrained users.

In this study, the emphasis is on fundamental manual dexterity requirements within highly dexterous environments, rather than delving into aspects of system design. The focus is specifically on discerning the differences in manipulation and monitoring behaviours between experts and novices in remote robotic operation. The objective is to elucidate the impact of expertise on remote operation, particularly in non-automated processes. The experiments involved the participation of four experienced (expert) and six trainee (novice) telerobotic system operators. Measurements were obtained as participants endeavoured to complete a set of tasks. Various operational and user parameters were measured, and statistical analyses were conducted to identify any significant differences between the expert and novice groups.

II. Related work

Studies focused on motor performance measurements generally analyse various objective metrics such as time [7], [8], path length, or number of movements [9], [10]. Additionally, they investigate the user's field of view (gaze) through eye tracking [11].

Eye tracking is widely utilized across various fields to analyse human behaviour and cognitive processes. In robotic surgery, researchers have used eye tracking to assess surgeons' workload, gaze patterns, and visual attention distribution during laparoscopic operations [12], [13], [14]. Studies have shown that expert surgeons tend to focus more on task-relevant areas with longer fixation durations and shorter saccade durations compared to novices [15]. Similarly, in aviation, eye tracking has been instrumental in highlighting differences in monitoring behaviour between experienced pilots and novices [16], [17]. Eye tracking has also been applied in the field of driving to evaluate hazard perception and driver behaviour [18], [19], [20]. These studies underscore the versatility and importance of eye tracking as a tool for understanding human cognition and performance across various domains.

In remote robotic operations, situation awareness (SA) and workload are essential for ensuring operational safety and optimizing human performance [21]. These concepts are widely acknowledged across various industries, including healthcare [22], [23], [24], transportation [25], [26], aviation [27], [28], and telerobotics [29], [30]. Generally, in such studies, self-reporting methodologies such as the Situation Awareness Rating Technique (SART) [31], [32] and NASA Task Load Index (TLX) [33] are utilized. For an instance comparison or validity of these approaches, see [34], [35].

III. Methods

A. Participants

The study participants were employees and secondees from the Department of Remote Applications in Challenging Environments (RACE) within the UK Atomic Energy Authority (UKAEA). The group mainly consisted of engineers, technicians, and operators who had prior experience and familiarity with teleoperation.

A total of ten users (1 female and 9 male) participated in the study. They were categorized into two groups: novice and expert. The novice participants had an average of 9 months of experience in teleoperation, while the experts had around 5 years of experience.

The procedures avoided invasive or potentially dangerous methods. Data were stored and analyzed anonymously. All participants provided written informed consent.

B. Experimental setup

The experimental consisted of a dual hand Telbot bilateral teleoperation system, see Fig. 1, Tobii gaze tracking glasses, and questioners to the participants after completing the experiment.

The Telbot system is a bilateral telerobotic system equipped with remote manipulators that offer seven degrees of freedom and can carry loads of up to 20 kg at their end effectors. These manipulators are controlled by local robots that are kinematically similar, each featuring six degrees of freedom. Human operators manage these local robots, ensuring precise and responsive control [36]. Five cameras are positioned on the remote side, as shown in Fig. 2, capturing images that are then projected onto monitors in front of the operators, including the HMI of the telerobotic system as shown in Fig. 1 (top).

We captured the robotic system's internal sensory information using the OPC Unified Architecture (OPC-UA) protocol, with a sampling frequency of $f_s = 1\,\mathrm{kHz}$. Eye movements were recorded using the Tobii Pro Glasses 3, a wearable mobile eye-tracking system that samples eye positions at 50 Hz. The recordings were analysed using Tobii Pro Lab software [37]. To minimize experimenter effects, such as "eye-tracker awareness" [38], operators received no instructions other than to perform their tasks as usual. Also, throughout the study, data on operators' task duration and errors were recorded. Subsequently, operators were asked to complete questionnaires regarding telerobotic handling qualities.

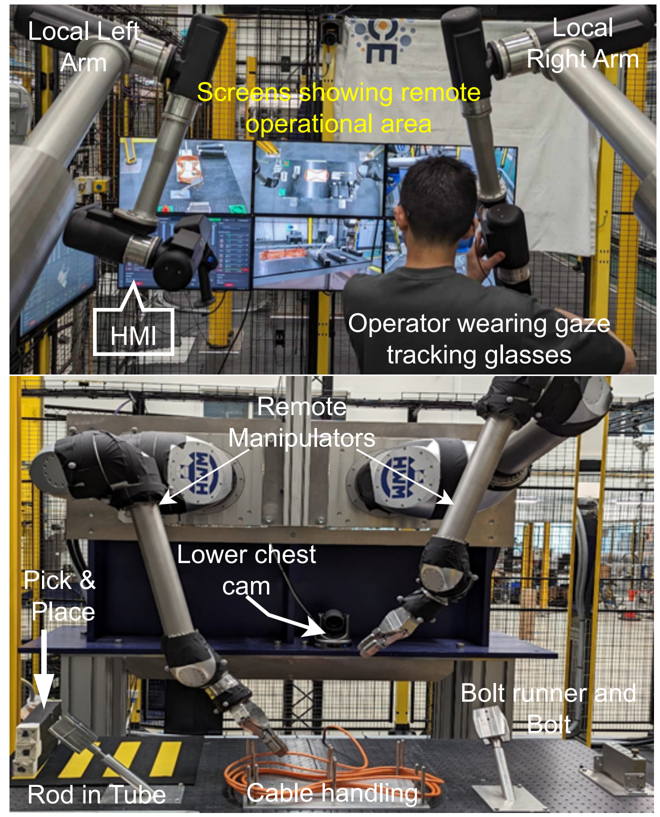

Fig. 1. Telbot dual hand bilateral telerobotic system: the top view depicts the local side, while the bottom view shows the remote side, featuring various tasks used in the experiments.

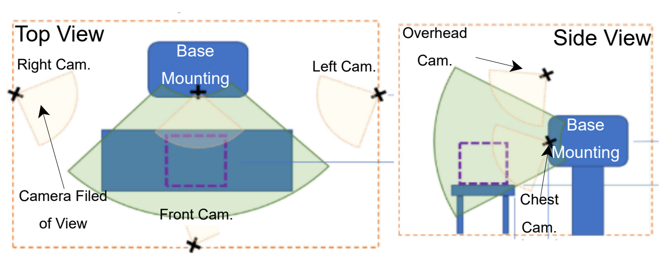

Fig. 2. Illustrative top down and side view of remote manipulators cell showing camera positions.

C. Experimental procedure: Tasks

While giving priority to accuracy and considering time, the operators were asked to complete five different tasks. These tasks do not precisely replicate the actual activities undertaken during remote robotic operation. Instead, they capture the key constraints and parameters.

- **Pick and Place:** Aim to evaluate the controllability and transparency of force feedback within the telemanipulator system. This task centers around manipulating blocks of similar size and visual appearance, yet composed of distinct materials (i.e., different weights as $50\,\mathrm{g}$, $2\,\mathrm{kg}$, $6\,\mathrm{kg}$). Initially, these blocks are stacked at a designated starting point. The primary goal is to correctly position the blocks in their designated spots from the stacking location, taking into account their individual weights. Following the determination of the placement sequence, the user is then required to return the blocks to the original stacking location.

- **Rod in Tube:** This task assesses both the user's capability and the manipulator system's proficiency in aligning a dowel (or rod) into a hole. The arrangement comprises a rod and a tube, as seen in Fig. 1, where the length of the rod surpasses $100\,\mathrm{mm}$ and the tube length extends beyond $80\,\mathrm{mm}$. Participants are tasked with accomplishing this assignment utilizing their right-hand arm/device, all while avoiding the jamming or wedging of the rod and refraining from exerting undue force on either the rod or the tube. The plate that holds the tube will be firmly affixed to the surface, positioning the tube at a $90°$ phase angle relative to the robot's base.
- **Bolting:** This test involves two blocks connected by a dowel, with the upper block designed to accommodate a bolt, and the lower block featuring a tapped hole. A single M10 remote handling-style bolt is used for this specific task. Participants are instructed to fully tighten the bolt, ensuring that excessive torque is avoided and cross-threading is prevented. After completing the tightening phase, participants must then disengage and reengage the bolt, carefully undoing it and returning it to its initial position.
- **Cable Handling:** This task replicates remote cable handling activities, emphasizing the need for precise and direct manipulation of cables using grippers to prevent any damage. The evaluation involves a $10\,\mathrm{m}$ length of standard multi-core electrical cable with a $7\,\mathrm{mm}$ diameter, including a remote-handleable connector at one end (refer to Fig. 1). The cable is initially wound onto a fixture, and participants are assigned the challenge of unwinding the cable and neatly arranging it on either the left or right side of the fixture.
- **Wire Loop:** The wire loop game, commonly referred to as a buzz wire challenge, involves users navigating a metal loop (referred to as a 'probe') along a winding path of wire without making contact between the loop and the wire, see Fig. 3 [39]. In this task, a power source connects the loop and wire, creating a closed electric circuit. If the loop and wire come into contact, the closed circuit triggers a response in the form of activating a light and sound-emitting device. Consequently, when the loop and wire touch, the light-emitting device illuminates, and the sound-emitting device emits a distinct sound, typically resembling a buzzing noise. Participants were given instructions to grasp the probe and skilfully navigate it through the loop (from right to left and reverse via changing arm/device), aiming to minimize contact with the wire. The objective of this challenge is to assess the positional accuracy and sensitivity of the overall system.

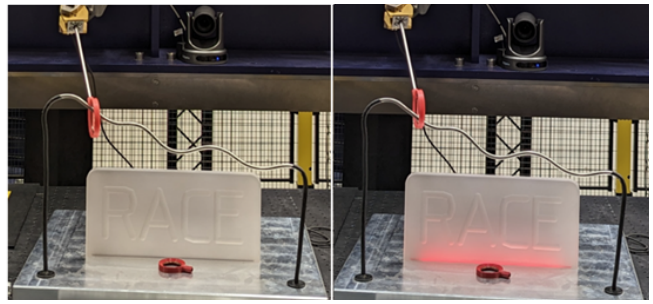

Fig. 3. The wire loop game; when the probe (metal loop) makes contact with the wire, the light-emitting device will illuminate (as depicted in the image on the right), accompanied by a buzzing sound from the sound-emitting device.

D. Manipulators' Motion

Throughout the tasks, the remote manipulators began from identical initial positions. Employing the recorded joint angles, we calculated the total path length (Δ_e) covered by the remote manipulators' end-effectors, the average manipulability ($\overline{\mu}$), and assessed trajectory smoothness using the jerk. The total path length is determined as follows:

$$\Delta_e = \sum_{k=1}^{n-1} \sqrt{(x_{k+1}-x_k)^2 + (y_{k+1}-y_k)^2 + (z_{k+1}-z_k)^2}\ ,$$

where x, y, and z are end-effector position with respect to the base and n is the maximum number of recorded sample.

Dexterity plays a crucial role in remote handling, enabling the serial manipulator to execute complex tasks without encountering joint limits. The manipulability index, μ, serves as a proxy for measuring the dexterity of the feasible configurations of the manipulator. For non-redundant manipulators, it can be expressed as:

$$\mu = \sqrt{\det(J(q)J(q)^\top)} = \prod_i \sigma_i\ ,$$

where σ_i denotes the singular values for the Jacobian matrix ($J(q)$) [40].

Agile and smooth point-to-point movements are crucial for operational safety. By examining the jerk of the end-effector, one can assess the smoothness of the tip trajectories in the operational space [41]. The jerk can be derived through the Jacobian matrix and its time derivatives:

$$\hat{j}_e = \ddot{J}(q)\dot{q} + 2\dot{J}(q)\ddot{q} + J(q)\,\dddot{q}\ .$$

IV. Main Results

The duration of task completions, as well as any errors encountered during pick-and-place and wire loop tasks, were investigated. Additionally, remote manipulator motions, including manipulability, jerk, and total path length, were analysed across all experimental tasks.

Meaningful differences in task duration and remote manipulator motion across expertise levels were assessed through statistical analyses on all groups. Normality tests were performed on the data groups, and for those failing the initial test, Box-Cox transformation was applied (with the same λ used for transformation across compared groups). Subsequently, all groups passed the normality tests at a significance level of $p = 0.05$.

The influence of expertise in dual comparisons, such as task completion duration and expert-novice correlations, was analysed using Welch's t-test (implemented in Matlab using $ttest2()$). A significance threshold of $p = 0.05$ was consistently employed for all statistical tests in the paper.

A. *Duration of Task Completion and Error Analyses*

Typically, it's expected that task completion time will decrease with increasing experience. However, it's crucial to note that task completion duration alone does not offer a comprehensive measure of performance. For example, experienced operators often prioritize error prevention over speed, resulting in a more balanced assessment of their proficiency.

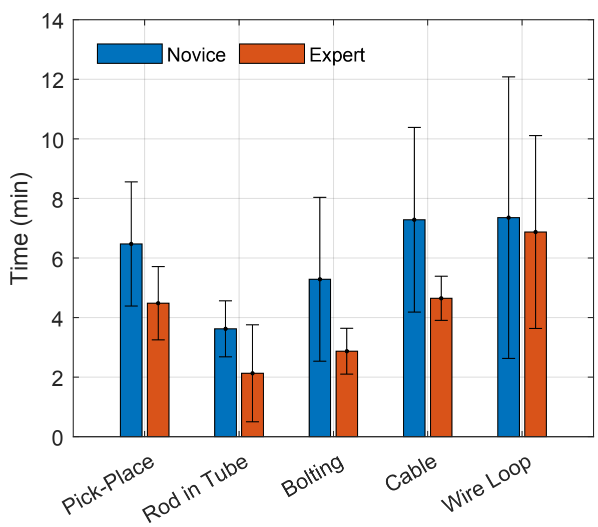

Fig. 4. Average task durations for each group.

Fig. 4 depicts the average task durations for each group, highlighting the notable trend that experienced users tend to complete tasks more swiftly. However, it's evident that there's considerable variability among users, which is underscored by the substantial standard deviation shown in the figure.

The analyses indicate a statistically significant difference ($p = 0.0132$) in task completion durations between experts and novices. More specifically, experienced users consistently complete all five tasks 2.6 min faster compared to novice users.

The average errors (standard deviation) committed by each group were analyzed in two tasks: pick and place, and wire loop. In the wire loop task, recorded errors indicate instances where participants made contact between the probe and the wire. For the pick and place task, the numbers represent how often blocks were inaccurately positioned, reflecting difficulty in discerning the weight differences.

TABLE I
AVERAGE (STD) ERROR MADE BY EACH GROUP IN TWO TASKS; PICK & PLACE AND WIRE LOOP.

Subject Group	Tasks	
	Pick and Place	Wire Loop
Novice	0.33 ($\pm$0.51)	22.33 ($\pm$3.61)
Expert	0.75 ($\pm$0.50)	7.5 ($\pm$5.44)

In the wire loop task, expert users not only completed the task more rapidly but also made fewer mistakes compared to novice users, as detailed in Table I. Conversely, in the pick and place task, expert users exhibited a higher frequency of errors. Specifically, they encountered difficulty distinguishing the weights of the light and medium blocks. This difference may be attributed, as mentioned by experienced operators during interviews, to the extensive experience they have with the MASCOT system [42], which reflects less electromechanical impedance to the operators compared to the system under consideration.

B. *Motion of the Remote Manipulators*

The average calculated total path length, manipulability, and jerk for each task is illustrate in Fig. 5.

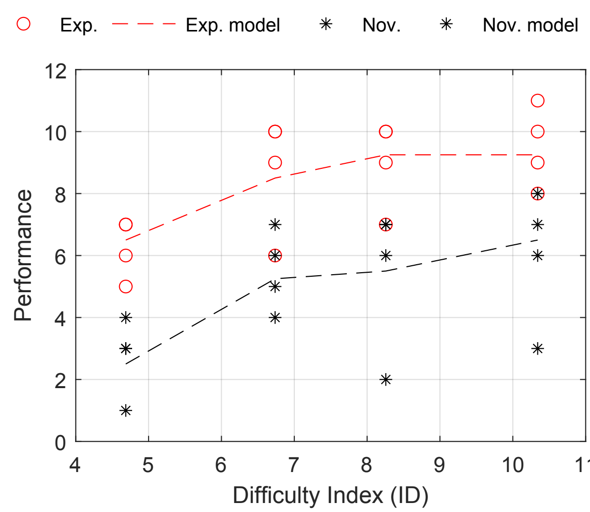

Fig. 5. Average total path length, manipulability, and jerk at teach task among the groups.

Expert users clearly perform fewer motions with the remote manipulators, evidenced by a statistically significant difference ($p = 2.1415 \times 10^{-5}$) in remote manipulator displacement when compared to novice operators.

Furthermore, expert operators tend to position remote manipulators closer to the centre of the workspace compared to novice operators. This is reflected in a statistically significant difference ($p = 0.000172$) in remote manipulator's average manipulability between expert and novice operators.

Moreover, not only do expert operators control remote manipulators with less displacement and optimal postures, but they also execute smoother movements. This is supported by a statistically significant difference ($p = 0.000365$) in remote manipulator's total jerk when comparing expert and novice operators.

C. Gaze Tracking

In our study utilizing gaze tracking, our primary aim was to capture the focal points of trained operators as they navigated through multiple screens (compensating for the lack of depth perception), buttons, and tools to perform specific tasks. The gaze heat-map for the tasks, illustrated in Fig. 6, offered insights into the distinct approaches employed by expert and novice operators. Previous studies have suggested that fixation duration, representing the total time spent in fixations, reflects the information processing load and tends to increase with workload [12]. Here, similar to [12], the absolute fixation duration time is scaled to a percentage of the exercise duration as

$$FD(\%) = \frac{\text{Sum of fixation duration}}{\text{Exercise duration}} \times 100.$$

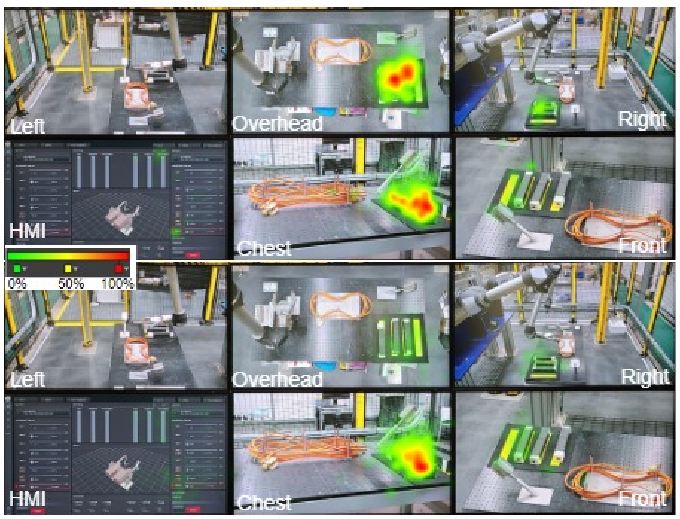

Fig. 6. Operators gaze heat-map during the experiments: top expert and bottom novice.

In the pick-and-place task, expert operators demonstrated a focused strategy, precisely placing each block using both overhead (top middle in the display matrix) and chest (bottom middle) cameras. Novice operators, on the other hand, predominantly relied on the chest camera, see Fig. 6.

For the rod-in-tube task, novice operators tended to inspect the rod angle by utilizing both the overhead and chest cameras to align it with the tube. In contrast, expert operators efficiently maintained the rod's position for pulling in/out, relying solely on the overhead camera. Novice operators placed greater emphasis on the front camera for pulling in/out the rod, while expert operators used it less frequently, relying on their expertise to complete the task smoothly.

In the cable handling task, expert operators leaned on the overhead camera for uncoiling, leveraging their familiarity with the task. Novice operators, however, tended to utilize both overhead and chest cameras for uncoiling, suggesting a need to check more cameras during the task.

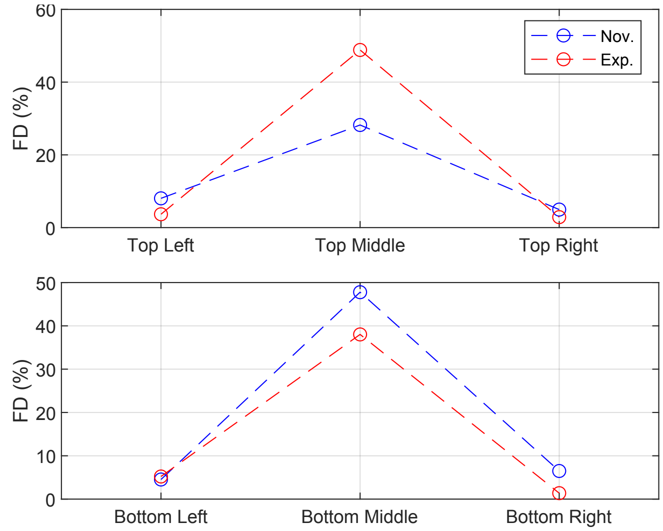

Fig. 7. Percentage fixation duration of novice and expert operators on various viewpoints.

For the wire loop task, expert operators heavily relied on both overhead and chest cameras, with relatively fewer views from the left and right cameras. Novice operators, while also using the overhead camera, needed to check the right and left cameras more frequently than their expert counterparts, potentially leading to additional time spent on camera checks to complete the task.

Fig. 7 shows the percentage fixation duration of novice and expert operators on various viewpoints. Novice operators mainly focus on the camera with a similar viewpoint to the users, while experts smoothly navigate through multiple angles. These findings highlight the different visual strategies used by expert and novice operators in bilateral telerobotic operations. Expert operators compensate for the lack of 3D perception by scanning multiple viewing angles continuously, while novices tend to focus mainly on the monitor displaying the same viewpoint. Intensive training and good hand-eye coordination are considered crucial for effectively scanning multiple viewing angles.

D. Questioners

After completing the experiments, participants were asked to fill out SART and NASA TLX questionnaires for each task they performed. These questionnaires assessed various categories, with participants providing ratings on a scale from 1 to 10 for:

- Mental, Physical, and Temporal demands, Performance, Effort, Frustration, Complexity, Arousal, Concentration of Attention, Information Quantity, and Familiarity.

Fig. 8 graphically represents the participants' responses. Across all tasks, participants consistently demonstrated high levels of concentration and arousal.

With the exception of the wire loop game, participants exhibited familiarity with the tasks. As a result, the mental, physical, and temporal demands were generally at a moderate level. It's noteworthy that task familiarity, regardless of complexity, influenced the amount of effort participants needed to exert to complete the task. The wire loop game stood out as the least familiar task for participants, resulting in elevated levels of mental, physical, and temporal demands, as well as increased effort and frustration.

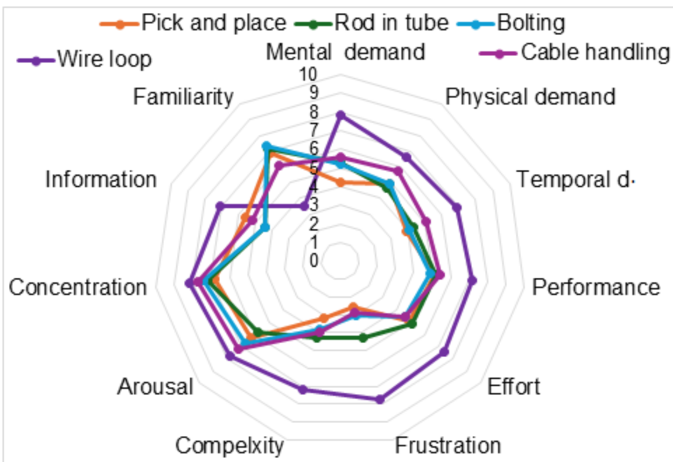

Fig. 8. Operators' response to the questions.

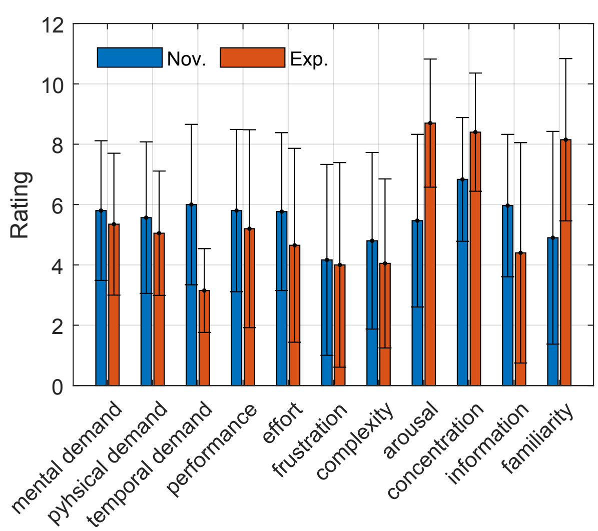

Fig. 9. Operators' response to the questions: novice vs expert.

Fig. 9 displays the user responses to the questionnaires categorized by their experience level. Overall, experts showed higher levels of arousal ($p = 0.0001$), concentration ($p = 0.0084$), and familiarity with the tasks ($p = 0.0034$), while novices reported higher temporal demand ($p = 0.0002$).

During the trials, it was observed that the majority of operators successfully completed tasks without errors, such as dropping blocks or jamming the rod. However, operators did not receive post-trial feedback on their performance, except for the wire loop game, where they could observe their mistakes. For instance, feedback on whether they managed to sort blocks according to their weights was omitted. In the questionnaires, most operators reported performing well during the trial, indicating a high level of self-assessment skill for remote telerobotic operations. Furthermore, the importance of training emerged in the questionnaires, with operators noting that they required more effort to complete tasks they were less familiar with.

V. Conclusion

Here, a user study was conducted to discern important parameters distinguishing an experienced person from a novice one while operating a complex bilateral telerobotic system. A variety of tasks were employed, covering essential parameters in force reflective teleoperation. It was found that task completion time, total path length, jerk, and manipulability of the remote manipulators are crucial criteria for operator assessments, as experts consistently outperform novice subjects. Additionally, experienced operators, who continuously scan multiple displays, compensate for the lack of depth perception compared to novice operators, who tend to focus on a single viewpoint similar to the users.

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