2022 IEEE International Conference on Robotics and Automation (ICRA)
May 23-27, 2022. Philadelphia, PA, USA

Comparison of Haptic and Augmented Reality Visual Cues for Assisting Tele-manipulation

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***Abstract*— Robot teleoperation via human motion tracking has been proven to be easy to learn, intuitive to operate, and facilitate faster task execution than existing baselines. However, precise control while performing the dexterous tele-manipulation tasks is still a challenge. In this paper, we implement sensory augmentation in terms of haptic and augmented reality visual cues to represent four types of information critical to the precision and performance of a tele-manipulation task, namely: (1) target location; (2) constraint alert; (3) grasping affordance; and (4) grasp confirmation. We further conduct two user studies to investigate the effectiveness and preferred modality of the sensory feedback against no sensory support, and how the preference will be influenced by the different types of simulated real-world additional workload. We asked 8 participants to perform a general manipulation task using a KINOVA robotic arm. Our results indicate that: (1) the haptic and AR visual cues can significantly reduce the task completion time, occurrences of errors, the total length traversed by the robot end-effector, the operational effort while increasing the interface usability; (2) the haptic feedback trended in the direction of presenting the information that needs a prompt response, while the AR visual cues are suitable to monitor the system status; (3) the participants chose their preferred feedback with the purpose of reducing the cognitive workload despite increased extra effort.**

I. Introduction

Robot teleoperation benefits from motion capture interfaces, which maps human motions to the teleoperated robots for freeform control. While being intuitive and efficient, such teleoperation interfaces are limited when required to control precise tele-manipulation tasks. Specifically, the precise control of the position and orientation of the robot end-effector and the manipulated objects usually lead to significant cognitive and physical workload, and may exhaust and frustrate the users novice to robot teleoperation. To increase the control precision, haptic and augmented reality (AR) visual cues can be introduced to communicate information critical to task performance, such as direction and distance to target, contact with object, and environment constraints. Although related work has proposed, evaluated, and compared various designs of haptic and AR visual cues, as well as their integration, there is still lack of design theory about what (types) of information are preferred to be communicated in which modality of sensory feedback. Moreover, it is also unclear how this preference will change in the presence of secondary tasks that demand additional cognitive workload (in terms of visual attention, haptic/proprioceptive perception, or critical thinking). Such design theory will contribute to the fundamental science of the design of multi-modal sensory feedback, and enable the design of haptic and augmented reality visual feedback to be generalized across robots, tasks and interfaces.

Fig. 1: Tele-nursing assistance tasks may involve freeform, dexterous manipulation (e.g., inserting a straw to the beverage container). Haptic and AR visual cues can be leveraged to communicate task-critical information.

The work in this paper focuses on the design of haptic and AR visual cues for assisting the dexterous freeform tele-manipulation tasks, performed in the context of tele-nursing assistance. Due to the recent COVID-19 crisis, many mobile manipulator nursing robots have been developed to perform remote patient care (e.g., serving food, beverage and medicine) and nursing assistance tasks (e.g., cleaning, organizing and preparation of nursing supplies). Unlike the very structured tele-surgical tasks, these nursing tasks usually do not follow a strict procedure, involve manipulation of a wide range of objects in cluttered environment, and therefore cannot be handled reliably by robot autonomy. To support such freeform tele-manipulation tasks, we propose haptic and AR visual cues to communicate the four types of information critical to the precision and success of general-purpose manipulation tasks, which were identified in our prior human factor experiment [1], [2]. This information, including 1) direction and distance to target, 2) environment constraints, 3) affordance of grasping, 4) contact with object, are provided in the reaching and grasping of objects within and out of the teleoperator's field of view. The haptic and AR visual cues are designed to be equivalent in their communicated information. Our user studies further compare the teleoperation performance, workload and preference using the *haptic* and *AR visual* cues, *with* and *without* additional workload of the secondary tasks. These secondary tasks are designed to simulate additional tele-nursing workload caused by visual monitoring of a patient's vital signs, perception of vibrotactile feedback from other wearable interface components, and critical thinking for patient evaluation. From the user studies we found out that: (1) both haptic and AR visual cues can effectively improve the efficiency, accuracy, usability and result in lower workload; (2) the haptic feedback is

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2022 IEEE International Conference on Robotics and Automation (ICRA) | 978-1-7281-9681-7/22/$31.00 ©2022 IEEE | DOI: 10.1109/ICRA46639.2022.9811669

suitable to represent the information that needs immediate attention, while the AR visual cue is preferred to show the continuous system status; (3) the preference of sensory feedback changes towards a combination that minimizes the cognitive workload with fewer sensory feedback overlap while involving the different types of secondary tasks. The contribution of this paper includes the design principles for sensory augmentation in terms of haptic and AR visual cues to support tele-manipulation using human motion tracking and the insight of how preferred sensory feedback changes to different types of cognitive workload when applied to real-world tasks thus furthering autonomous sensory integration design.

II. Related Work

A. Haptic and AR Visual Cues for Teleoperation Assistance

For decades, various haptic and AR visual cues have been designed, evaluated, and compared for a wide range of robot teleoperation tasks. Overall, haptic feedback (in terms of force and vibrotactile display) are usually used to communicate continuous feedback that requires time-critical response, yet the precision and the amount of information encoded are limited. On the other hand, AR visual cues can communicate very rich, detailed information using a variety of colors, shapes and displayed text. However, it takes more time for a human to respond to visual feedback (around 500 ms) and may cause visual crowding and distract the user's attention. As a result, haptic feedback has been widely used for driving assistance (e.g., safe lateral control [3], braking assistance [4], cruise control [5], curve negotiation [6], avoiding collision with obstacles and pedestrians [7], [8], etc) in terms of shared haptic control [9], as well as teleoperation assistance for mobile/wheelchair robots (e.g., trajectory guidance [10], [11], cooperative navigation [12], [13], etc.). For tele-manipulation tasks, haptic feedback in terms of virtual fixtures [14], [15] has many benefits in terms of control precision and manipulation safety [16], [17], user comfort [18], and coordination of multi-robot systems [19]–[21]. The fusion of force and tactile feedback can also enhance the remote perception for unknown object identification [22]. Meanwhile, AR visual cues are preferred to assist the estimation of spatial relationship (e.g., gap estimation for driving assistance [23]), to direct and enhance visual attention (of drivers [24], [25], and video game players [26]). More recently, AR visual cues are used to communicate the intent between humans and robots [27]–[29] and enable robot autonomy to become more explainable [30].

B. Multimodal Sensory Integration

The various designs of haptic and AR visual cues also enables the integration of multimodal sensory feedback, which is natural to human sensorimotor control. Indeed, the integration of visual and haptic feedback is critical to the precise manipulation tasks, because it plays an important role in perception of object shape [31]–[34] and object dynamics [35], and in the performance of precise pointing and grasping movements [31], [36], and in usage of (articulated) tools [37], [38]. Related work in literature has investigated the dominance, weighting and the roles of attention in human's integration of visual and haptic feedback [39], [40], and compared haptic and visual feedback for their effectiveness on body posture guidance [41], on the control of dexterous tele-manipulation [42], and motor learning [43]–[45]. Recent designs of sensory integration have integrated AR visual displays which visualize robot model and end-effector, or interaction force, with the haptic cues which indicate task guidance or constraints [20], [46]–[54]. Although these designs of haptic and AR visual cues, as well as their integration, have been validated to be effective in user studies, these designs and validations are mostly specific for tasks and robots. There is limited work that systematically investigated how the design of visual-haptic sensory integration depend on the nature of conveyed information and the modality that the information is conveyed through [54]. It is also unclear how the design of sensory integration should be changed if the robot teleoperator needs to perform secondary tasks that demand additional visual attention, awareness of the haptic/vibrotactile feedback from other wearable interfaces, or efforts for critical thinking.

III. Teleoperation Interface and Assistance

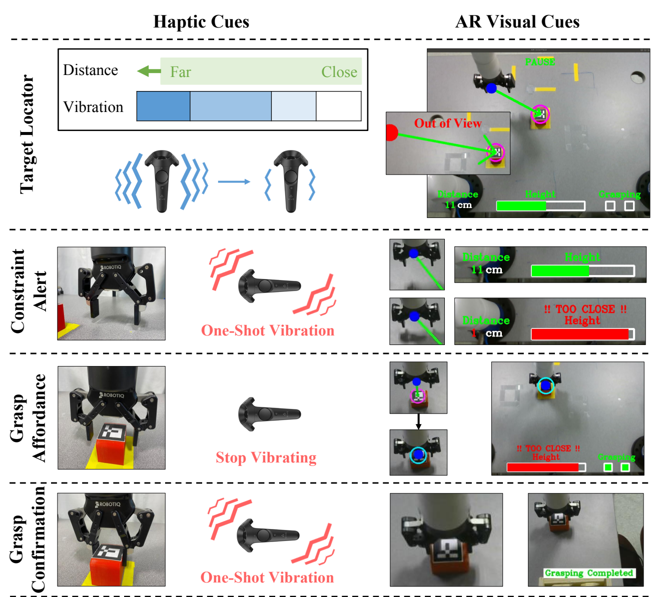

Fig. 2: Design of equivalent haptic and AR visual cues, for the target locator, constraint alert, action affordance, and grasp confirmation.

This section will present our design of the motion tracking interface for robot teleoperation, as well as the haptic and AR visual cues for tele-manipulation assistance. Shown in Fig. 1, we used the hand pose tracked by the hand-held controller of HTC Vive virtual reality system to control the end-effector of a Kinova Gen 3 robotic manipulator. The hand-held controller provides programmable vibrotactile feedback, while AR visual cues are augment the video stream of the remote workspace camera.

We proposed the four types of tele-manipulation assistance based on the findings from our prior human factor experiments [2], [55], which investigated the visual-haptic sensory integration in the usage of active telepresence. Shown in Fig. 3, participants with a head-mounted display can select the video stream from the wearable cameras attached to their head, torso and arms for visual feedback, which simulates the active telepresence cameras typically available in robot teleoperation tasks. The participants also wore thick gloves so that they could only feel the contact with objects and environment, which simulates the limited haptic feedback available in robot teleoperation. Our prior study observed how the participants perform a general-purpose manipulation task that integrates reaching, moving, grasping and stacking actions, after adapting to the new visual and haptic feedback. We found out that: 1) after some practice, participants can seamlessly integrate the usage of active telepresence cameras with the actions to perceive haptic feedback; 2) the typical actions to leverage the limited haptic feedback include touching-to-locate objects, moving the objects on the table (instead of above the table) to take advantage of the table constraints; 3) when performing the manipulation tasks, participants leverage active telepresence cameras and haptic feedback to locate the target, detect environment constraints, examine possible grasp, and confirm the contact with an object. These observations inspired the design of haptic and AR visual cues for sensory augmentation (as shown in Fig. 2), which include:

Target Locator indicates the robot end-effector's movement direction and distance to the goal (i.e., the targeted object). As the robot end-effector approaches the targeted object, the haptic cue decreases the strength of its continuous vibration, while the AR visual cue uses a green vector to visualize the ideal direction of motion of the robot end-effector (the blue dot) and its distance to the target (the distance in centimeters at the bottom left of the screen). The marker on the robot end-effector will turn red and increase the diameter to alert the user that the robot is out of view and provide the exact direction to support the self-correction.

Constraint Alert alerts the teleoperator if the end-effector is about to violate any environment constraints (e.g., hitting the table), in which case the haptic cue vibrates the hand-held controller, while the AR visual cue monitors the robot end-effector's height from the table and turns from green to red if too close to the robot. The height indicator bar also fills up with increased proximity to the table.

Grasp Affordance indicates if the end-effector is posed to be ready to grasp the target object, which can be generalized to indicate if the robot end-effector is ready to afford the action to be performed. When the robot end-effector is ready to grasp, the hand-held controller will stop to vibrate, while the AR visual cue will highlight two boxes if the end-effector is within the target region and the height is low enough.

Grasp Confirmation indicates that the robot end-effector has successfully grasped the target object, using a one-shot vibration of the hand-held controller, while the AR visual cue will display "Grasp completed" and hide all the other AR visual cues. This indicator can be generalized to confirm any completed action.

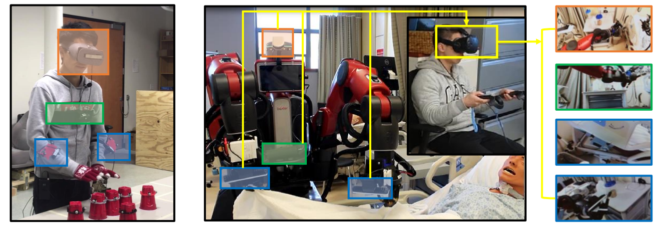

Fig. 3: Our prior human factor experiment that investigated the visual-haptic sensory integration in the usage of active telepresence cameras [2], [55].

IV. Experiment

Participants and Research Questions: We conducted two user studies (with the same 8 participants, 5 males, 3 females, age = 30.5$\pm$3) to investigate the following research questions: (**RQ1**) How effective these haptic and AR visual cues can support tele-manipulation? (**RQ2**) Which modality of sensory feedback people prefer to use to communicate what types of information for tele-manipulation support? (**RQ3**) How this preference will be influenced by the different types of workload introduced by the the secondary tasks performed along with the robot teleoperation?

Experimental Procedure and Conditions: Fig. 4 shows the experimental procedures for User Study I and II. The User Study I includes a *training phase* and an *evaluating phase*. During the training phase, participant first learned the baseline interface (i.e., tele-manipulation via hand motion tracking), the haptic and AR visual feedback augmented interfaces from the verbal instructions and demonstrations of an experimenter, and then practiced for five minutes each. During the following *evaluation phase*, participants performed three sections of a reaching-and-grasp task, in which they controlled the remote robot manipulator to grab a small wood block in the workspace (see Fig. 1). We randomized the order of the sections using different modes of sensory feedback, namely no feedback, haptic, and AR visual feedback. In each section, the robot end-effector was set to be at three different starting locations, which were close to the target, far away from the target, and out of the camera view, respectively. The participants manipulated the object for three repetitions for each robot starting location. In User Study I, the participant performed a total of 27 trials (3 modes of sensory feedback $\times$ 3 robot starting locations $\times$ 3 repetitions).

In User Study II, participants teleoperated the robot to perform a primary task of picking-and-place an object into three different bins (shown in Fig. 4), for two sessions. The participants performed the task first in Session 1 using the baseline interface (hand motion tracking without haptic or AR visual feedback), and then performed the task again in Session 2 using their preferred form of sensory feedback for the four types of tele-manipulation assistance. In both Session 1 and 2, we introduced three types of secondary tasks to robot tele-manipulation in a randomized order, to understand how they may change the performance, workload, and preference of sensory feedback. As shown in Fig. 5 (top), the *haptic monitoring* task requires the participants

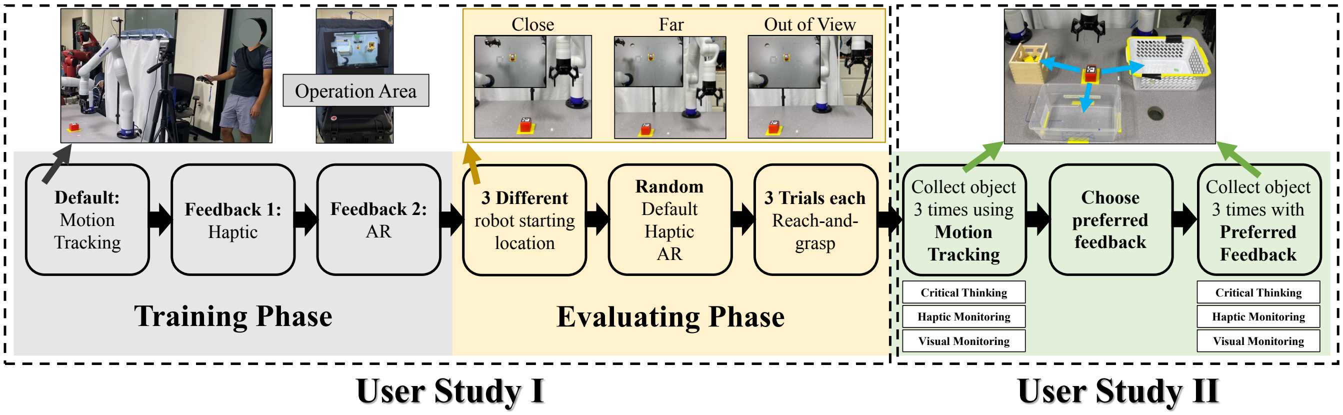

Fig. 4: Experiment procedure.

to press the button of the controller held in their non-dominant hand within 1 second if they detect any vibration from it. The one-shot vibration occurs randomly every 7 to 13 seconds during the tele-manipulation task. The *visual monitoring* task (bottom in Fig. 5) requires the participants to monitor the simulated vital sign profile displayed in the second user interface. About every 5 seconds, the displayed vital sign goes beyond its normal range (60 to 100) and turns red, and the participants have 1 second to press the button of the controller held in their dominant hand (same controller for robot operation) to record this event. Moreover, we designed a *critical thinking* task which requires the participants to verbally respond to simple math problems (only includes addition and subtraction of one digit numbers) continuously while performing the tele-manipulation task. These secondary tasks were designed to simulate the additional cognitive workload that healthcare workers may experience when performing the patient care tasks along with nursing robot teleoperation, including the haptic perception for standing by the emergency on-call, the visual attention for monitoring patient status, and the critical thinking for patient evaluation.

Evaluation Metrics: In both User Studies I and II, we measured the task completion time, and types and occurrence of errors (e.g., hitting the object, collision with the table), to evaluate task performance. In User Study I, we collected the length of the trajectory traversed by the robot end-effector. The participants also filled out the NASA-TLX survey on a scale from 1 to 20, the System Usability Scale (SUS) survey on a scale of 0 to 100 and answered our customized survey questions on the preferred modes of sensory feedback. In User Study II, we took quantitative and objective measurements of the cognitive workload, using the time to respond to and the success rate of the secondary tasks. Specifically, we measured the time to respond to each math question, and the occurrence of pressing the button correctly in response to haptic and visual monitoring tasks. We also recorded the choices between haptic and AR visual cues for each of the four types of tele-manipulation support for each secondary task.

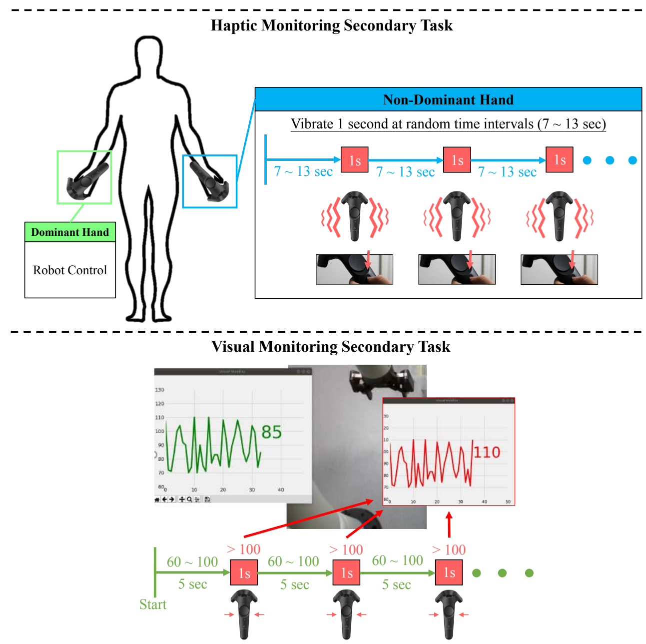

Fig. 5: Secondary tasks that introduce additional cognitive workload for haptic monitoring (top) and visual monitoring (bottom).

V. Results

A. User Study I: Comparison of Sensory Feedback

Fig. 6 to 8 compares tele-manipulation tasks performed with and without the haptic or AR visual cues. Fig. 6 shows the mean and variance of the task completion time and trajectory length across all the trials and participants, for different starting locations of the robot end-effector. To some extent, the AR and haptic cues reduced the task completion time. Based on the one-way analysis of variance (ANOVA), the haptic cues and AR visual cues significantly reduce the task completion time for far-away ($F(1,46)=5.1$, $p<0.05$) and out-of-view starting point ($F(1,46)=6.68$, $p<0.05$), respectively. ANOVA analysis showed the significant difference in trajectory length between baseline and with haptic feedback ($F(1,46)=42.99$, $p<0.05$) for close starting location. While the AR visual cues had significantly shorter trajectory length than baseline and haptic feedback for close ($F(1,46)=63.49$, $p<0.05$; $F(1,46)=17.63$, $p<0.05$), far-away ($F(1,46)=4.87$, $p<0.05$; $F(1,46)=3.39$, $p<0.05$) and out-of-view (F(1,46)=5.2, p<0.05; F(1,46)=3.45, p<0.05) starting locations.

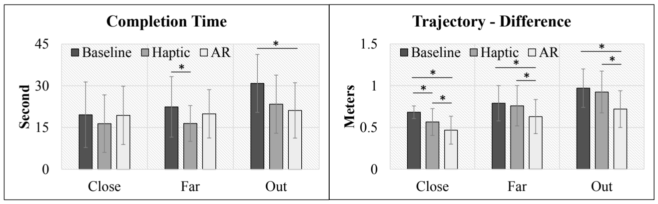

Fig. 6: Task completion time and trajectory.

In Fig. 7 we compared the total occurrence of errors from all the participants and trials, because the mean and variance of the error across participants and trials were consistently small. For the table collision, the mean and standard deviation of occurrences for baseline, haptic and AR visual cues are (close: 0.75±0.43, far-away: 0.88±0.44, out-of-view: 0.67±0.47), (close: 0.13±0.33, far-away: 0.08±0.27, out-of-view: 0.17±0.37) and (close: 0.42±0.49, far-away: 0.54±0.49, out-of-view: 0.46±0.49). While for the hitting target object, the mean and standard deviation of occurrences for baseline, haptic and AR visual cues are (close: 0.33±0.47, far-away: 0.42±0.49, out-of-view: 0.33±0.47), (close: 0.2±0.41, far-away: 0.38±0.48, out-of-view: 0.29±0.45) and (close: 0.04±0.19, far-away: 0.08±0.38, out-of-view: 0.04±0.2). Across all the starting points, the haptic cues consistently performed better than AR visual cues in avoiding the collision with the table, while the AR visual cues can better prevent hitting the targeted object compared to the haptic cues. This implies that AR visual cues may be more suitable to avoid errors in the operation of the target objects, which the teleoperator needs to continuously track with visual attention, while the haptic cues are preferred to alert the teleoperator of the environmental constraints as needed to avoid visual distraction.

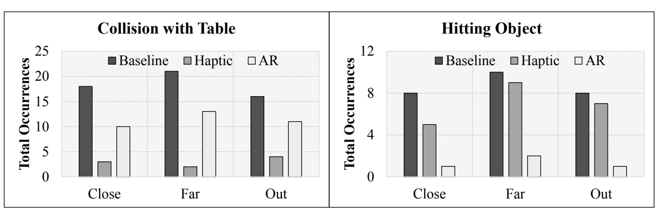

Fig. 7: Occurrences of collision with table and hitting object.

We use the weighted NASA-TLX scores to measure the subjective workload across baseline, haptic and AR visual cues. The weighting coefficients were selected as follows: mental demand=5, physical demand=1, temporal demand=0, performance=4, effort=3, frustration=2. Based on the Wilcoxon rank sum test, the feedback from the NASA-TLX and the SUS survey (Fig. 8) further indicated that both the haptic and AR visual cues had significant lower workload (p<0.05) and higher usability scores (p<0.05) than the baseline condition without any sensory augmentation cues. We also noticed consistency in the preference of sensory feedback for different types of tele-manipulation assistance: 6 out of 8 participants prefer to use AR visual cues for the *target locator* and *grasp affordance*, and use haptic cues for the *constraint alert* (7 out of 8 participants) and *grasp confirmation* (6 out of 8 participants).

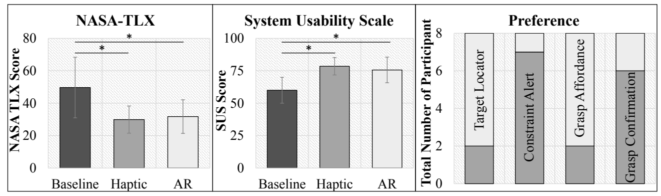

Fig. 8: Feedback of NASA-TLX, SUS and user preference survey.

B. User Study II: Adaptation to Secondary Tasks

Fig. 9 and 10 compared the performance of the primary and secondary tasks without the augmented sensory cues, and with the user's preferred sensory cues, for tele-manipulation performed with different types of secondary tasks. Note that the participants can choose different sensory modes for each of the four types of tele-manipulation assistance. Fig. 9 shows the mean and variance of the task completion time, which indicates significant performance improvement (p<0.05) for all the secondary tasks using the preferred sensory modes. Moreover, the preferred sensory mode reduced the total errors from all the participants in all the trials. The reduction for the collision with the table is much more obvious compared to that for hitting the target object.

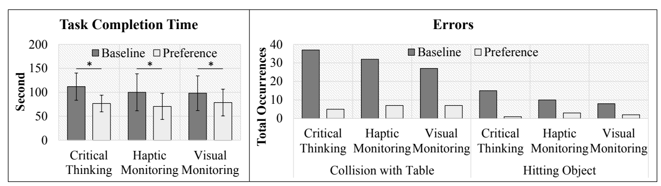

Fig. 9: Primary task completion time and error occurrences.

Fig. 10 shows the preferred sensory modes also significantly improved (p<0.05) the performance of the secondary tasks by 1) reducing the time to respond to the math problems simulating the critical thinking workload, and 2) improving the success rate in the tasks of visual and haptic monitoring.

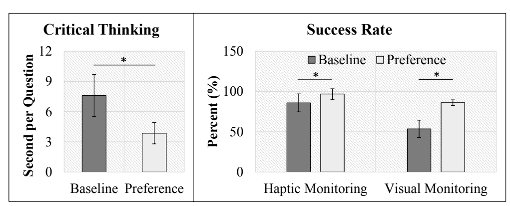

Fig. 10: Performance of secondary tasks.

Fig. 11 shows the number of users that prefer haptic versus AR visual cues for each tele-manipulation assistance, when the tele-manipulation was performed with each secondary task. We noticed that for critical thinking and haptic monitoring, the users' preferences fell into two categories with a 5:3 or 4:4 ratio, while for visual monitoring there is a tendency that the users prefer haptic cues more than the AR visual cues, with a 6:2 ratio for three out of four tele-manipulation assistance. This tendency in the preference may be because the haptic cues do not compete with the primary task for visual attention.

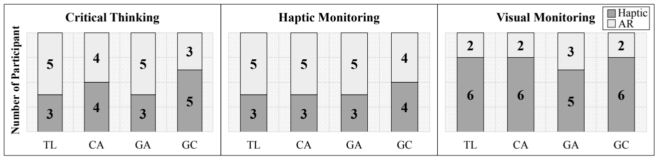

Fig. 11: Preferred sensory modes for target locator (TL), constraint alert (CA), grasp affordance (GA), and grasp confirmation (GC).

VI. Discussion

A. Benefits of the Haptic and AR Visual Cues

In terms of objective task performance and subjective workload evaluation, our results demonstrate the potential benefit of haptic and AR visual cues to represent the information critical to the tele-manipulation task. Participants using haptic feedback significantly outperformed the baseline interface when the robot started from the far-away condition, showing a 27% decrease in completion time. While the AR visual cues also significantly outperformed the baseline interface when the robot starting from the out-of-view condition, showing a 32% decrease in time taken. This finding implies the desired autonomy in switching the mechanism of sensory feedback based on the visibility of the robot platform in the remote user interface. Whereas for the robot starting from the close condition and the rest of the comparison not mentioned before, our work does not support a significant difference between the haptic, AR visual cues and baseline without any sensory feedback. It is possible that, for the close condition, the distance between the robot end-effector and the target object is not enough to exaggerate the significant difference but the haptic cues still trended in the lowest completion time. As the task performance has been improved by introducing the haptic and AR visual cues, our subjective evaluation results show a comparable reduction in operational workload and addition on system usability. These findings answer our research question (**RQ1**) that the haptic and AR visual cues can effectively benefit the tele-manipulation task.

B. Design Philosophy for Sensory Feedback

In this paper, we implemented the haptic and AR cues upon the baseline motion tracking teleoperation interface to communicate four critical information of tele-manipulation tasks. We categorized the information into two groups, the information needs the user to take immediate action (e.g., environment constraints, grasp confirmation) and the information to serve as the status monitoring (e.g., direction and distance to target, affordance of grasping). Participants using haptic feedback demonstrated the lowest accumulated occurrences of table collision across all the robot starting locations which was also supported by their subjective preference. Participants also reported that using haptic feedback can increase the awareness of the sense that they do grasp the object. While the participants using AR visual cues significantly reduced the length of the robot trajectory and the occurrences of hitting the object. Many participants reported that the AR visual cues transfer the alignment of the grasping to a game-like task which simplifies the precise manipulation. Based on these objective findings and preferences from participants, our research question (**RQ2**) have been answered and also helped us to conclude a philosophy for sensory augmentation design: the haptic/vibrotactile feedback may encode the information that requires prompt attention and AR visual feedback may present the continuous system status.

C. The Impact of Additional Workload

In practice, the nurses need to take care of multiple requests and tasks at the same time and results in adding more cognitive workload while performing the healthcare services. To investigate how the preference of sensory feedback will be affected by different types of workloads, we introduced three different types of secondary tasks to simulate the potential extra workload for nursing application include critical thinking (decision-making), haptic monitoring (other medical devices or emergency on-call) and visual monitoring (patient vital signs). The post-study preference survey indicated that the sensory feedback selection changed toward choices of feedback that had fewer shared cognitive workload with secondary tasks (e.g., more participants chose AR visual cues over the haptic feedback in haptic monitoring secondary task, and vice versa). Many participants explicitly stated that the same sensory feedback between assistance and the secondary task will confuse the operation and result in a higher mental workload. This finding answers our research question (**RQ3**) that the preference of haptic and AR visual cues switch to the purpose of avoiding the cognitive workload intersection while demanding extra effort.

VII. Conclusion, Limitations and Future Work

This paper proposed a generalizable sensory augmentation design to assist dexterous tele-manipulation tasks. The designs well-supported the findings in our prior human factor experiment that investigated the visual and haptic sensory integration in the usage of active telepresence cameras for general-purpose manipulation. We also conducted systematic evaluation to compare the sensory augmentation using haptic and AR visual cues, and investigate how the users' preference of sensory modality may be affected by the secondary tasks that introduced different types of cognitive workload. From the two user studies, we found out that both participant performance and participant workload were improved with the haptic and AR visual cues over the baseline without sensory feedback. Also, the preference of the sensory integration tended to avoid the feedback overlap when involving the different types of secondary tasks. The studies in this paper are limited because the sample size is small, and the participants are from the general-public population instead of the current and future primary users of the tele-nursing robot interfaces. Our future work will recruit more participants who are registered nurses, nursing students and faculty. We will also develop autonomous sensory integration based on human intent, different types of manipulation tasks, environments, and the phase of the task.

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