Navigation and Cognitive Load in Telepresence Robots*

Grace Pan[1] and Thea Weiss[2] and Seyed Amirhosein Mohaddesi[3] and John W. Szura[4] and Jeffrey L. Krichmar[1,3]

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Abstract— **Telepresence robots have become integrated into educational, medical, and workplace settings as the capabilities of remote technologies progress. Considering the recent pandemic, the deployment of telepresence robots to digitally represent individuals in remote environments has become more important. The goal of this study was to investigate if implementing autonomous features, such as navigation, in telepresence robots could reduce cognitive load and facilitate operation for the user. While many studies involving telepresence robots examine navigation, there has been little research on how different types of navigation affect cognitive load and user experience. The present study measured differences between autonomous and manual navigation on cognitive load, spatial awareness, presence, and user experience during a scavenger hunt task using a telepresence robot. We found that in the autonomous navigation condition, participants moved around their environment more efficiently, performed better in a learning and memory task, and had lower cognitive load assessments than those in the manual navigation condition. These results suggest that incorporating autonomous navigation functions into telepresence robots may lessen cognitive load, enabling individuals to attend to more stimuli in their environment and improve learning in educational settings.**

I. INTRODUCTION

With both the rise of the robotics industry and the recent pandemic, there is an increased demand for remote technologies such as telepresence robots [1], [2]. With the limitations placed on social gatherings, telepresence robots have become a valuable option for in-person meetings and communication. Telepresence robots continue to be used to participate and interact with others in various settings like schools, hospitals, and workplaces [3], [4]. There is a clear market for these telepresence technologies, and as telepresence becomes more widespread, enhancing certain experiences like ease of use and mobility have become imperative to telepresence functionality and acceptance.

A key aspect for improving the telepresence experience is to decrease the cognitive load needed to operate the robot. Cognitive load is defined as the amount of working memory being occupied. Reducing cognitive load during teleoperation may free users to better attend to tasks and people in their environments [5]–[7]. Since cognitive load pertains to how much information is present in working memory at one time, experiencing a high cognitive load could negatively impact an individual's learning and attention to salient stimuli [8].

To examine the effects of navigation type on cognitive load, our study measured cognitive load and performance on a search task while operating a telepresence robot requiring manual operation or allowing the robot to navigate autonomously. Our experimental study followed a dual task design and consisted of a primary task and a secondary task, which is illustrated in Fig. 1.

The present study contributes to the study of including remote technology into the workplace or school by:

- Introducing a spatial working memory task to assess cognitive load.
- Including gold standard assessments for cognitive load, presence and affect.

We find that adding autonomous features, such as path planning and navigation, to telepresence robots can make the following contributions:

- Reduced cognitive load during operation.
- Improved learning on working memory tasks.
- Faster task completion times.

In general, we suggest that adding autonomous features can increase the adoption of remote technologies into the classroom, office, and home.

II. RELATED WORKS

Studies have investigated how providing telepresence robots with autonomous functions can affect the user experience [9], [10]. Similar to the focus of the present work, these studies examined how to better integrate telepresence robots into social settings and improve user experience. Batmaz and colleagues found that automatic speed control could simplify navigation and decrease cognitive load, but the decision to implement this was left to the user's personal preference [9]. Their findings are similar to our results in that while participants had reduced cognitive load operating the robot autonomously, some preferred manual navigation because they enjoyed controlling the robot. However, while Batmaz et al. speculated that automatic speed control would reduce cognitive load, they did not directly test this themselves, and they did not analyze emotional affect while navigating. In the present study, we employed standard measures of cognitive load with NASA-TLX, a more subjective measurement of

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[1] Grace Pan is with the Department of Cognitive Sciences, University of California, Irvine, Irvine, CA, USA `gypan1@uci.edu`

[2] Thea Weiss is with the Department of Psychology, University of Washington, Seattle, WA, USA `tweiss1@uw.edu`

[3] Seyed Amirhosein Mohaddesi is with the Department of Computer Science, University of California, Irvine, Irvine, CA, USA `smohadde@uci.edu`

[4] John Szura is with the School of Education, University of California, Irvine, Irvine, CA, USA `jszura@uci.edu`

[1,3] Jeffrey Krichmar is with the Department of Cognitive Sciences and Department of Computer Science, University of California, Irvine, Irvine, CA, USA `jkrichma@uci.edu`

At which location on the map did you find this face? *

1. Use GUI to locate face (marked with X)
2. Navigate to face (auto or manual).
3. Locate face.
4. Remember face and its location.

Fig. 1. Experimental design for testing cognitive load during telepresence robot operation. **1.** Participants accessed a GUI remotely. **2. and 3**. The participant began with a scavenger hunt to locate and navigate to each face, marked with an “X” on the GUI map, using manual or autonomous controls. **4.** After the participant found all the faces, they completed a secondary memory task to match the faces to their location. Following the learning and memory task, they were instructed to fill out self-report questionnaires to assess workload, feeling of presence, and affect.

cognitive load, and a secondary learning and memory task, which is a more objective measurement of cognitive load [11]. Furthermore, we examined participants’ emotional affect while operating the robot using the PANAS assessments.

Prior studies have investigated if autonomous navigation features could improve the telepresence experience. Takayama and colleagues investigated how autonomous features might improve the telepresence experience [12]. Autonomous-assisted obstacle avoidance lowered the number of errors, but interestingly, increased completion times. Unlike the present study, there were no differences in most of the NASA-TLX measurements between the autonomous and the manual groups. This may be due to the absence of a cognitive task, such as the present scavenger hunt which impacted cognitive load, and by creating an additional dual task to further measure cognitive load. Similar to the present study, Pang and colleagues found that autonomous navigation decreased the task completion time and lowered NASA-TLX scores [13]. However, their task involved the robot follow an interactant rather than specifically testing participants on a cognitive task. Kiselev and colleagues evaluated autonomous navigation in their telepresence study [14]. However, the main focus of the study was whether novice users would adopt these features.

Yang and colleagues found that personality and presence were strongly conveyed through the telepresence robot, but there were strains on other aspects of interaction like responsibility, dependency, and contribution [10]. While there were similarities with our results, their study did not measure cognitive load or implement different types of navigation in telepresence robots.

Thus, an important contribution of the present study is relating the inclusion of autonomous features with a cognitive task like the spatial memory and face recognition task introduced here. The dual-task design of including a secondary learning and memory task provides more robust measurements of cognitive load than previous studies also examining different navigation types and cognitive load. Furthermore, we included standard load and affect assessments that further supported our hypothesis that autonomous features can reduce cognitive load when using telepresence robots.

III. METHODS

A. *Participants and Recruitment*

Participants included 11 males and 11 females (n=22) between the ages of 18 and 48. They were recruited through digital and physical flyers posted on the University of California, Irvine (UCI) campus. Experimental procedures were approved by the Institutional Review Board (IRB) at UCI. Due to the Covid-19 pandemic, participants accessed a Toyota Human Support Robot (HSR) remotely by logging onto the laptop containing the robot’s user interface via the TeamViewer remote desktop software. There were no in-person experimental sessions. Before beginning the experiment, participants filled out pre-study questionnaires for video game experience, telepresence robot experience, locus of control and mental rotation assessment task. We note that the pre-study responses had no effect on experimental results and therefore are not reported. Upon completing the experiment, participants were compensated for the study in the form of a gift card, or course credits granted by the UCI Human Subjects Lab Pool.

B. *Telepresence Robot and Environment*

The Toyota Human Support Robot (HSR) and its associated Robot Operating System (ROS) packages were used for this study [15]. The HSR was designed to help with household tasks for the elderly and impaired [16]. Prior to the study, we mapped the floor of a university building using an existing SLAM algorithm [17]. ROS libraries provided with the HSR were used to plan paths. The robot’s Lidar and camera detected obstacles and the path planner changed its route appropriately. The robot’s onboard computer handled the mapping and navigation. A laptop computer mounted on the back of the robot contained the user interface that mapped button clicks to robot movements of the body and head (Fig. 2). The camera feed from the robot was also visible on the Graphical User Interface (GUI). The software for controlling the robot was written in Python.

Participants accessed the HSR by logging onto the laptop via the TeamViewer remote desktop software. This allowed them to see the GUI and have access to the laptop’s mouse and keyboard. The experimenter held an additional laptop (see Fig. 3), which the participant connected to via Zoom

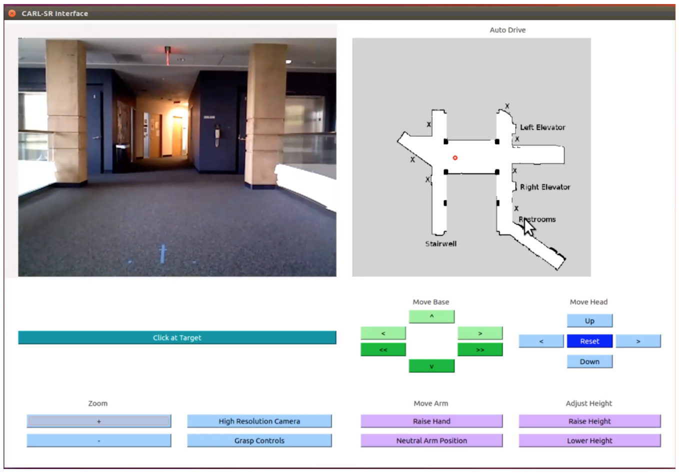

Fig. 2. GUI to control the Toyota HSR. The top left image is the HSR camera feed. In the manual navigation condition, participants clicked on the green and blue buttons under the "Move Base" and "Move Head" functions to move the HSR. In the autonomous navigation condition, participants clicked on the white space on the map (top right) and the HSR planned a path to the desired location. The desired location was marked with a green circle while the real-time location of the robot was marked with a red circle. The "X" marks on the map indicate where each cartoon face was located.

videoconferencing software so there could be communication with the experimenter if necessary. The participant shared their screen, which allowed the experimenter to see the participant's viewpoint.

C. Procedures

Participants were given instructions on how to connect to TeamViewer and how to gain access to the HSR user interface by remotely controlling the GUI for the robot. Once connected, they underwent a short training session where the participants learned how to navigate the HSR using both autonomous and manual controls. In the autonomous navigation condition, participants were instructed to click on the white space on the map (Fig. 2, top right) causing the HSR to move to that location. The HSR planned a path to the desired location while avoiding obstacles. In the manual navigation condition, participants were instructed to use the green and blue buttons under the "Move Base" and "Move Head" functions to move the body and the head of the HSR (Fig. 2, bottom right). They could also use the keypad on their computer to move the robot (to move the head: "A" - move the head to the left, "D" - move the head to the right, "W" - move the head up, "S" - move the head down; to move the body: up arrow key - move the base forward, left arrow key - rotate the base to the left, right arrow key - rotate the base to the right). As soon as participants felt comfortable with the controls, the experimenter put up a set of cartoon faces at each "X" location on the map (Fig. 2, top right) to begin the experimental session.

Note that we did not consider using a joystick since many potential telepresence users and robot platforms do not have this option available [3]. Furthermore, data was collected during the height of the COVID-19 pandemic. The university was closed with the exception of required experimental personnel. Participants were remote and inaccessible. Requiring a joystick would have reduced participation.

Fig. 3. HSR reaching a face location via telepresence operation. An experimenter, shown in the figure, was present to assist the remote participant if necessary.

The primary task was a scavenger hunt. Seven cartoon faces were placed around the floor of an office building and participants used the controls of their assigned navigation condition (autonomous or manual) to move to each "X" on the map. In the autonomous navigation condition, they could only click on the map to move the body of the HSR, but once they were at the desired location, they could move the HSR's head using the blue buttons in the GUI to look around their environment. In the manual navigation condition, they could only use the GUI's blue and green buttons or the keyboard to move the robot. They would use their assigned navigation controls to locate the face and to bring the face into "speaking distance" (close enough to see the features of the face through the HSR camera) at each of the seven "X" locations on the map (Fig. 3).

After completing the primary experimental task (the scavenger hunt), participants returned to the experimental session Google Forms link where they completed a secondary task. The secondary task was an image spatial learning and memory task where participants had to match the faces to their locations during the scavenger hunt (Fig. 4). Seven of the cartoon faces were target faces used in the scavenger hunt, and three of the cartoon faces were distractors that shared similar features to the target faces but were not used in the scavenger hunt. They had to match the correct face to the correct location or respond "none" if the face was not present in the scavenger hunt.

After participants finished these assessments, they moved on to the second experimental session where they repeated the process but used a different type of navigation and a

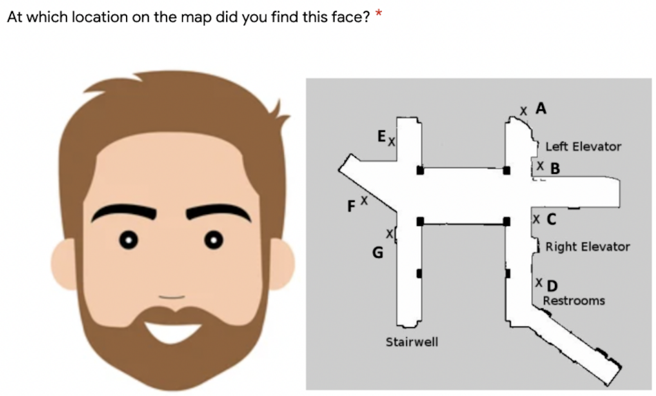

Fig. 4. Secondary learning and memory task example. Participants were instructed to match the face to the correct location on the map, and if the face was not present during the scavenger hunt, they should mark "none."

different set of faces. The order of the autonomous and manual conditions was randomly assigned. Participants were also randomly assigned to begin with either Set A or Set B faces in the first experimental session and then switched to the other set of faces in the second experimental session. No order effects due to navigation mode or face sets were observed.

D. *Cognitive Load Assessments*

Following the secondary task, participants completed the NASA-TLX [18], [19], Presence [20], [21], and Positive and Negative Affect Schedule (PANAS) [22] self-report questionnaires. These assessments were used to additionally measure cognitive load and user experience after each experimental session. The NASA-TLX is a multi-dimensional scale designed to obtain workload estimates from operators after performing a task. The subscales include mental, physical, and temporal demands, frustration, effort, and performance. The assumption is that some combination of these dimensions are likely to represent the workload experienced by most people performing most tasks. Following [21], we used a questionnaire to measure presence of participants when operating the HSR. Presence is defined as the subjective experience of being in one place or environment, even when one is physically situated in another. The PANAS is a 20-item self-report measure affect. Positive affect is associated with pleasurable engagement with the environment, whereas negative affect reflects a dimension of general distress summarising a variety of negative states such as anger, guilt, or anxiety.

E. *Statistical Tests*

The data collected was not normally distributed. Therefore, the Wilcoxon signed-rank test, a non-parametric statistical hypothesis test, was used to compare the medians between the autonomous and manual conditions.

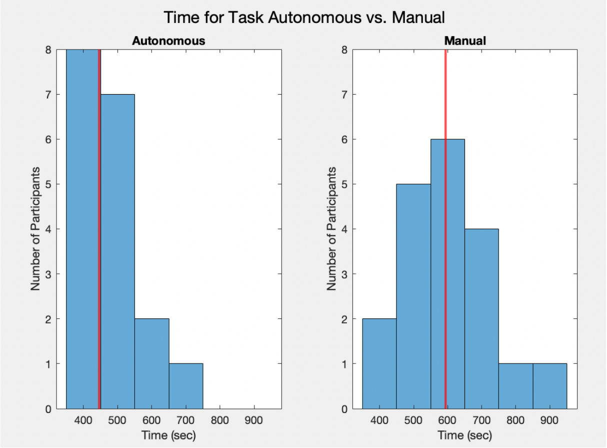

Fig. 5. Time to complete the scavenger hunt task for autonomous navigation condition and manual navigation. The red line is the median of the distribution.

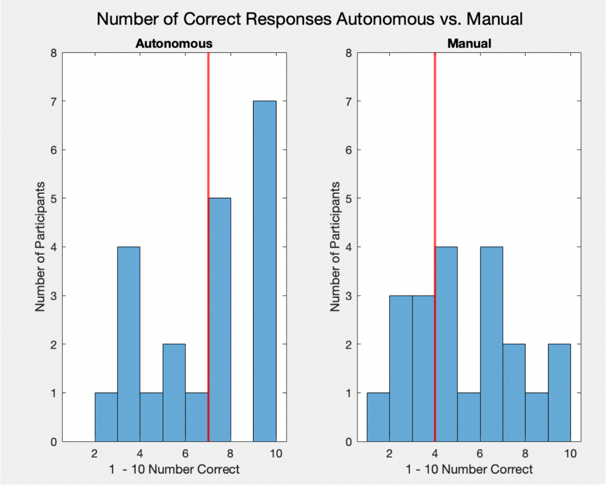

Fig. 6. Performance on the secondary learning and memory task measured by the number of correct matches of faces to locations in each condition.

IV. RESULTS

A. *Cognitive Load Effects on the Learning and Memory Task*

In cognitive tasks, the time spent on a task can act as a measure of cognitive load [23]. Fig. 5 shows that participants were significantly more efficient when navigating the HSR autonomously during the primary spatial memory task where they had to find all the faces (p-value < 0.0001; Wilcoxon signed-rank test). These results indicated that participants were faster completing the experimental task in the autonomous navigation condition than in the manual condition. Since stimuli were in working memory for a shorter duration, this may have contributed to a decrease in cognitive load.

Fig. 6 shows that participants had more correct responses during the secondary task where they matched cartoon faces to their locations in the autonomous navigation condition (p-value < 0.05; Wilcoxon signed-rank test). These results indicate that autonomous navigation may reduce cognitive load and lead to improved learning in spatial recognition tasks.

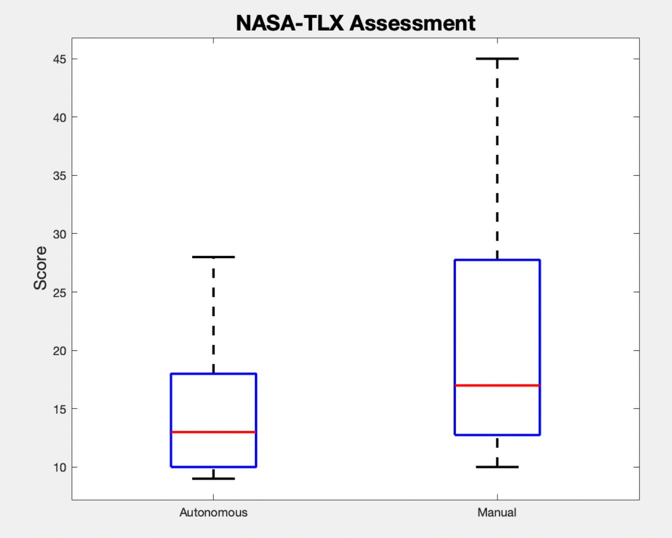

Fig. 7. NASA-TLX assessment of cognitive load. In each box plot, the red central mark indicates the median, and the blue bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers.

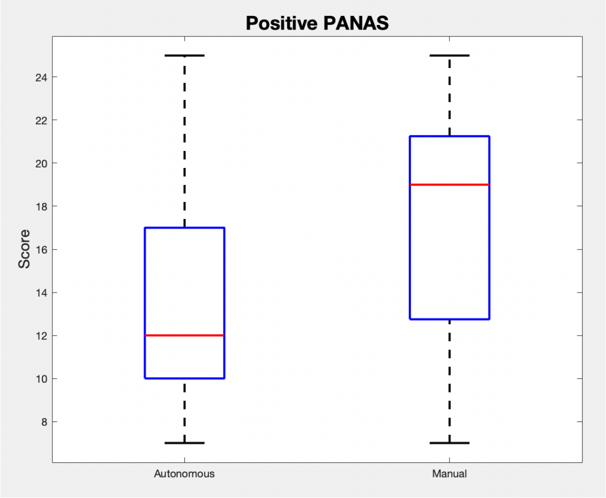

Fig. 8. Positive PANAS scores for participants in the autonomous and manual navigation condition.

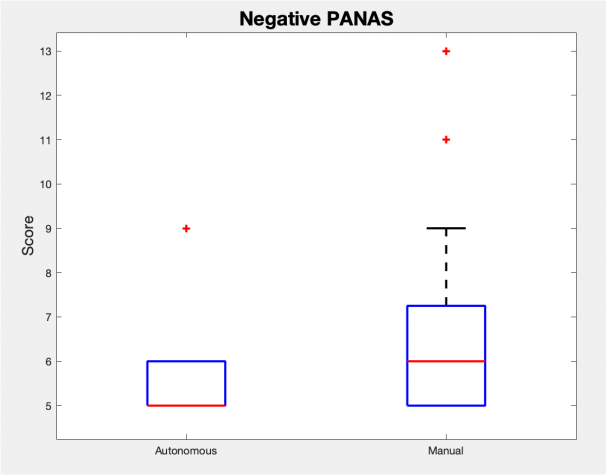

Fig. 9. Negative PANAS scores for participants in the autonomous and manual navigation condition. The red plus signs in the boxplot indicate outliers, which are values that are more than 1.5 times away from the 25th or 75th percentile.

B. Cognitive Load and User Experience Assessments

In addition to the time taken and correct responses in the primary and secondary experimental tasks, reduced cognitive load during the autonomous condition was indicated through participant responses on the NASA-TLX assessment which was given immediately after each (i.e., autonomous and manual) scavenger hunt session. The NASA-TLX scores shown in Fig. 7 indicate that cognitive load was lower in the autonomous navigation condition than the manual navigation conditions (p-value < 0.0005; Wilcoxon signed-rank test).

Emotional affect has been shown to compete with working memory and may become extraneous cognitive load [24].The positive and negative affect levels were lower in the autonomous navigation condition than in the manual navigation condition (Figs. 8 and 9), suggesting that subjects experienced fewer distractions that interfered with their task performance when using autonomous navigation. The positive PANAS score was higher when operating the HSR manually suggesting that participants experienced more positive emotions by being in control (p-value < 0.005; Wilcoxon signed-rank test). However, the negative PANAS score was also higher in the manual condition, possibly indicating frustration or anxiety during HSR operation (p-value < 0.05; Wilcoxon signed-rank test). Potential accidents and collisions in the environment during manual operation can elicit more emotions and anxiety from the participants [10]. Although there were very few collisions, subjects may have feared that a collision was imminent when operating the robot manually. This could in turn require more engagement and concentration on moving the robot rather than memorizing face locations.

Telepresence robots can provide feelings of presence and embodiment for the user [10]. There were no significant Presence score differences between the manual and autonomous conditions (p-value > 0.10, Wilcoxon signed rank test). Therefore, despite allowing the HSR to plan the paths to locations, participants still felt present in the environment. Showing the robot view during movement and having the ability to communicate may contribute to the embodied experience.

V. DISCUSSION

The aim of this study was to test whether using autonomous navigation in telepresence robots could decrease cognitive load and thus improve learning in educational settings. The use of a novel scavenger hunt task and the secondary facial recognition task, which were complemented by standard cognition and affect assessments, provided a test of learning and memory under different telepresence conditions. Autonomous navigation may have reduced cognitive resources being allocated to obstacle avoidance and path planning, which in turn may have facilitated performance on the secondary learning and memory task. Decreasing the cognitive load required to operate telepresence robots and increasing the ease of use may encourage the integration of these technologies into classrooms, homes, and workplaces.

One principal advantage of telepresence robots is the feelings of presence and embodiment that they offer [10]. Participants reported no significant difference in feelings of presence between the autonomous and manual navigation conditions, which indicates that including autonomous navigation controls can serve to improve the usability of telepresence robots without taking away from the feelings of being present in their environment.

Future studies should include various other telepresence robots to test the validity of the results. This would allow us to examine if these results and some of the complications were specific to the Toyota HSR or if they universally impact teleoperation devices. Prior studies do suggest that manual operation of other telepresence robots is a limitation [3], [4]. These experiments should be run with participant's having access to a joystick during manual operation. However, as mentioned before, this is not an option for many potential users [3] and situations like a pandemic lockdown may make this difficult. Furthermore, the university lockdown meant that there we no moving obstacles (e.g., people) during the experiment. It would be interesting to re-run this experiment in a dynamic setting to see how that makes a difference in performance. Overall, the results of this study suggest that autonomous navigation in telepresence robots like the Toyota HSR is an effective tool in decreasing cognitive load and improving the overall usability of telepresence robots in day-to-day interactions.

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REFERENCES

[1] L. Hung, J. Wong, C. Smith, A. Berndt, M. Gregorio, N. Horne, L. Jackson, J. Mann, M. Wada, and E. Young, "Facilitators and barriers to using telepresence robots in aged care settings: A scoping review," *J Rehabil Assist Technol Eng*, vol. 9, p. 20556683211072385, 2022.

[2] B. Isabet, M. Pino, M. Lewis, S. Benveniste, and A. S. Rigaud, "Social telepresence robots: A narrative review of experiments involving older adults before and during the covid-19 pandemic," *Int J Environ Res Public Health*, vol. 18, no. 7, 2021.

[3] V. Ahumada-Newhart and J. S. Olson, "Going to school on a robot: Robot and user interface design features that matter," *ACM Trans. Comput.-Hum. Interact.*, vol. 26, no. 4, p. Article 25, 2019.

[4] V. Newhart and M. Warschauer, "Virtual inclusion via telepresence robots in the classroom: An exploratory case study," *The International Journal of Technologies in Learning*, vol. 23, no. 4, pp. 9–25, 2016.

[5] P. Ayres, "Impact of reducing intrinsic cognitive load on learning in a mathematical domain," *Applied Cognitive Psychology*, vol. 20, no. 3, pp. 287–298, 2006. [Online]. Available: https://doi.org/10.1002/acp.1245

[6] T. de Jong, "Cognitive load theory, educational research, and instructional design: some food for thought," *Instructional Science*, vol. 38, no. 2, pp. 105–134, 2010. [Online]. Available: https://doi.org/10.1007/s11251-009-9110-0

[7] A. S. Yeung, P. Jin, and J. Sweller, "Cognitive load and learner expertise: Split-attention and redundancy effects in reading with explanatory notes," *Contemporary Educational Psychology*, vol. 23, no. 1, pp. 1–21, 1998.

[8] J. Sweller, "Cognitive load during problem solving: Effects on learning," *Cognitive Science*, vol. 12, no. 2, pp. 257–285, 1988.

[9] A. U. Batmaz, J. Maiero, E. Kruijff, B. E. Riecke, C. Neustaedter, and W. Stuerzlinger, "How automatic speed control based on distance affects user behaviours in telepresence robot navigation within dense conference-like environments," *PLoS One*, vol. 15, no. 11, p. e0242078, 2020. [Online]. Available: https://www.ncbi.nlm.nih.gov/pubmed/33211736

[10] L. Yang, B. Jones, C. Neustaedter, and S. Singhal, "Shopping over distance through a telepresence robot," *Proc. ACM Hum.-Comput. Interact.*, vol. 2, no. CSCW, p. Article 191, 2018. [Online]. Available: https://doi.org/10.1145/3274460 https://dl.acm.org/doi/pdf/10.1145/3274460

[11] S. E. Bijarsari, "A current view on dual-task paradigms and their limitations to capture cognitive load," *Frontiers in Psychology*, vol. 12, 2021. [Online]. Available: https://doi.org/10.3389/fpsyg.2021.648586

[12] L. Takayama, E. Marder-Eppstein, H. Harris, and J. M. Beer, "Assisted driving of a mobile remote presence system: System design and controlled user evaluation," *2011 IEEE International Conference on Robotics and Automation*, pp. 1883–1889, 2011.

[13] W. C. Pang, G. Seet, and X. Yao, "A study on high-level autonomous navigational behaviors for telepresence applications," *Presence*, vol. 23, no. 2, pp. 155–171, 2014.

[14] A. Kiselev, A. Kristoffersson, F. Melendez, C. Galindo, A. Loutfi, J. Gonzalez-Jimenez, and S. Coradeschi, "Evaluation of using semi-autonomy features in mobile robotic telepresence systems," in *2015 IEEE 7th International Conference on Cybernetics and Intelligent Systems (CIS) and IEEE Conference on Robotics, Automation and Mechatronics (RAM)*, 2015, pp. 147–152.

[15] M. Quigley, K. Conley, B. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, and A. Y. Ng, "Ros: an open-source robot operating system," *ICRA workshop on open source software*, vol. 3, no. 3.2, p. 5, 2009.

[16] T. Yamamoto, K. Terada, A. Ochiai, F. Saito, Y. Asahara, and K. Murase, "Development of human support robot as the research platform of a domestic mobile manipulator," *ROBOMECH Journal*, vol. 6, no. 1, p. 4, 2019. [Online]. Available: https://doi.org/10.1186/s40648-019-0132-3

[17] S. Kohlbrecher, O. v. Stryk, J. Meyer, and U. Klingauf, "A flexible and scalable slam system with full 3d motion estimation," *2011 IEEE International Symposium on Safety, Security, and Rescue Robotics*, pp. 155–160, 2011.

[18] S. G. Hart, L. E. Staveland, P. Hancock, and N. Meshkati, *Human mental workload*. Amsterdam: North-Holland, 1988.

[19] S. G. Hart, "Nasa-task load index (nasa-tlx); 20 years later," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 50, no. 9, pp. 904–908, 2006. [Online]. Available: https://doi.org/10.1177/154193120605000909

[20] A. Sutcliffe, B. Gault, and J.-E. Shin, "Presence, memory and interaction in virtual environments," *International Journal of Human-Computer Studies*, vol. 62, no. 3, pp. 307–327, 2005.

[21] B. G. Witmer and M. J. Singer, "Measuring Presence in Virtual Environments: A Presence Questionnaire," *Presence: Teleoperators and Virtual Environments*, vol. 7, no. 3, pp. 225–240, 06 1998.

[22] D. Watson, L. A. Clark, and A. Tellegen, "Development and validation of brief measures of positive and negative affect: the panas scales," *J Pers Soc Psychol*, vol. 54, no. 6, pp. 1063–70, 1988.

[23] J. Lee, "Time-on-task as a measure of cognitive load in tblt," *The Journal of AsiaTEFL*, vol. 16, no. 3, pp. 958–969, 2019.

[24] J. L. Plass and S. Kalyuga, "Four ways of considering emotion in cognitive load theory," *Educational Psychology Review*, vol. 31, no. 2, pp. 339–359, 2019. [Online]. Available: https://doi.org/10.1007/s10648-019-09473-5