Assessing Limited Visibility Feedback for Overhead Manufacturing Assembly Tasks

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Abstract

Worker posture, task time and performance are often affected when one-handed manual dexterous tasks are performed in small overhead spaces under an obscured view. A common method used for supplementing visual feedback in these cases is a hand-held telescopic mirror, but that involves working with both arms extended overhead, and is often accompanied by awkward neck and shoulder postures. A video camera was considered as an alternative to using a mirror for visual feedback and reducing overhead reach. A mirror, a borescope and an omnidirectional camera were evaluated while laboratory participants performed three one-handed simulated manufacturing tasks in a small overhead enclosure. Videos were recorded for quantifying the time that postures were assumed while performing the tasks. The average time that both arms were above mid-shoulder height for the omnidirectional camera was more than 2.5 times less than for the mirror and borescope. The average proportion of neck strain time was 0.01% (or less) for both the omnidirectional camera and the borescope, compared to 83.68% for the mirror. No significant differences were observed in task completion times between the three modalities. Hence, an omnidirectional camera can provide visibility while reducing straining postures for manufacturing operations involving overhead work.

1. Introduction

1.1. Aerospace Manufacturing and Visually Obstructed Work

Aerospace manufacturing is often challenged with maintaining a balance between solving technical issues such as processing and assembling large-dimension products, and maintaining good ergonomics (Mueller et al., 2019). Manufacturing in this industry is associated with high physical and cognitive demands because it necessitates intense manual work for long hours. Manual work, including forceful exertions, awkward postures, vibration, and contact stresses, is associated with musculoskeletal disorder (MSD) risk (Barondess et al., 2001). Beuß et al. (2019) reported that worker postures inherent with aerospace manufacturing, especially during the final assembly, were related to MSD. Sustained postures and exertions in aerospace manufacturing were also associated with musculoskeletal symptoms (Kim & Nussbaum, 2019; Menegon et al., 2012). Gerr et al. (2013) reported significant association between neck and arm strain, and time-in-posture for musculoskeletal outcomes among manufacturing workers.

In many cases, aerospace assembly tasks are performed overhead and involve working with structures that are physically accessible but not clearly visible, causing the work to be partially or completely obscured. Such tasks commonly entail assuming extreme neck and arm postures in order to peer into the entry points and perform overhead work (Mueller et al., 2017; Palm et. al, 2018; Mueller et al., 2019). The obstacles associated with limited visual access often result in impaired task performance and completion time, which exacerbate the negative ergonomic outcomes. When posture and performance are negatively affected due to poor or partially obscured visibility, the worker may make their best attempt to gain a partial view, and in doing so, assumes straining positions. These constrained areas often have limited physical accessibility and only enough room to reach the hands and arms into a small space to perform a task, but not along with the head and shoulders. Working in these constrained areas may therefore cause mechanics to switch intermittently between their arms and hands to access the workspace and view the work with their heads to gain feedback and make any adjustments necessary. Consequently, the cognitive workload associated with the translation in space increases and has the potential for more errors and reduced quality when continually switching back and forth.

Although the nature of overhead tasks may require one arm in the workspace, the use of two arms increases the total strain. Additionally, instead of directly peering into an overhead workspace while assuming awkward neck postures, having a way to view the workspace at convenient neck postures could reduce neck and shoulder strain. A common method used for visual feedback in these cases is a hand-held telescopic mirror which requires both arms extended overhead. A potential solution to the ergonomic issues posed by these overhead workspaces is to provide visual feedback via a mobile camera that can be placed inside the workspace, relaying the visual field of the task to the worker. This paper considers two alternative modalities to the mirror for providing visibility while reducing neck and arm strain and enabling the worker to effectively perform the task: a borescope and an omnidirectional camera.

1.2. Mirrors

Mirrors are the most common tool used by aircraft manufacturing operators to gain visual access to structures located with limited visibility. They are also used for simple inspection tasks including examining the airplane surface for cracks and dirt (Drury & Watson, 2002). Common mirrors are telescopic and can be extended into constricted areas. The challenges of using mirrors include limited field of view, inadequate illumination, and hand-held control, often necessitating awkward body postures for viewing.

1.3. Borescopes

Borescopes are long tubular optical instruments containing a camera and built-in illumination. They facilitate visual inspection by reaching into obscure and narrow areas. In aircraft manufacturing, borescopes are used in maintenance to ascertain the quality of inaccessible structures. They are the main means to identify defects in areas of the aircraft that would otherwise be difficult-to-reach without disassembling the structure to gain access to the internal areas. Retrieving unfamiliar objects in airframes and engines is another use case (Stringfellow et al., 2004). Video borescopes have become popular because of their improved flexibility and ability to convert the actual view to a digital image (Aust et al., 2019).

While the borescope aids in obtaining visual access in convoluted structures such as the aircraft's engine turbines, there are many challenges associated with using a borescope, including controlling tip movement direction and the extent of the tip movement inside these structures. Moreover, the limited field of view of borescopes often results in loss of orientation and situational awareness, consequently leading to unsatisfactory task performance (Drury & Watson, 2001). For overhead workspaces, the hand-held use of borescopes may improve visibility, but no study has yet explored if they reduce stress and strain for overhead work.

1.4. Omnidirectional cameras

Omnidirectional cameras have been explored for applications ranging from mobile terrestrial mapping (Campos et al., 2018) to robot soccer (Nurrohmah et al., 2020). These cameras consist of multiple camera lenses that provide an omnidirectional view through the method of image stitching. The ability to provide a whole panoramic view with fewer blind spots compared to the conventional camera (Hirabayashi et al., 2020; Jayasuriya et al., 2020) is a common advantage of using omnidirectional cameras. The visual processing of a panoramic view might pose cognitive challenges in orientation and locating task activities. While presenting promising features for manufacturing, such cameras have seldom been used in this domain.

1.5. *Objectives*

It is hypothesized that if a borescope or omnidirectional camera is used to perform visually obscured overhead tasks, the duration of the neck and two-arm strain are reduced when compared to use of a mirror due to hands-free use and wide field of view. The decreased strain duration would result in improved usability and task effectiveness when compared to the other modalities. A laboratory simulation representative of an overhead aerospace manual assembly job was used to test these hypotheses using a mirror, a borescope, and an omnidirectional camera. Participants were recruited and performed simulated tasks representative of activities conducted under obscured visual conditions.

2. Methods

2.1. *Participants and Data Sources*

Twenty-one undergraduate students from the University of Wisconsin-Madison were recruited for the study (5 female, 16 male), ranging between 18 and 22 years. All participants were recruited via email lists obtained from the university student directory. Approval from the university Institutional Review Board (IRB) was obtained, and the participants provided informed consent to participate in the study. The level of manufacturing experience among the participants varied from none to tasks like soldering, riveting, grinding, and screwing.

2.2. *Study Procedure*

The study was conducted during a single session that lasted an average of 80 minutes. At the beginning of the session, the participants were asked to complete a demographic questionnaire consisting of questions related to their experience in manufacturing. Then, they performed three simulated one-handed manufacturing tasks: repetitive rivet insertion, wire connection, and pattern tracing. Each visual modality was used in a random order to prevent bias due to task learning effect. They were then asked to complete the System Usability Scale (SUS)

(Brooke, 1996), USE-Ease of Learning (Lund, 2001), and NASA TLX (Hart & Staveland, 1988) questionnaires for each modality, after performing all three tasks. SUS scores indicate modality usability, USE-Ease of Learning evaluates use the modality, and NASA-TLX scores indicate task mental workload. The participants also answered a semi-structured interview after using each modality. The interview consisted of questions related to the participants' experience using the modalities for completing the task, including the challenges they encountered. They were also asked about their modality preferences for each of the tasks performed. The session was completed with a questionnaire asking participants to rate the tasks based on difficulty and the modality preferred. All the interviews and videos of task executions were recorded for analysis.

2.3. Task Simulation

All three tasks were performed in an overhead wooden box, as shown in Figure1. A pictorial 2D representation of the interior of the box was shown to the participants prior to task execution. The box had a single ellipsoidal point of entry (major axis length=12.7 cm, minor axis length=7.62 cm), and was adjusted for every participant to a height of 7.5 cm above the head vertex. The ellipsoidal hole was similar in size and shape of access holes provided on aircraft structures for accessibility to manual work, based on access for mechanics and materials. The tasks consisted of rivet insertion, wire connection, and pattern tracing, which are representative of the kinds of activities performed in aerospace manufacturing.

Rivets are permanent mechanical fasteners and are among the most common fastener types in aircraft assembly. The repetitive rivet insertion task involved inserting two rivets, each of 0.635 cm diameter and 1.905 cm length, into specified holes. Each of these insertions were timed separately and were executed as two subtasks.

The wire connection task required connecting single and triple wire connectors located on one side of the box. The task was considered successful if both the wires were connected properly. If only one of the wires was connected, the task was rated as partially complete, and if none of the wires were connected, the task was considered a failure.

The pattern tracing task traced the bottom edge of cylindrical objects. These objects were comparable to 3.175 cm bolt heads. The task was intended to simulate sealant application performed during aircraft manufacturing. Performance was scored on a scale of three, based on the number of criteria satisfied: (1) the completeness of the traced circle, (2) the maximum deviation of the traced circle being less than 5mm and (3) the tightness of the traced circle compared to the circumference of the cylinder. Completeness of the traced pattern was determined by analyzing if the pattern was a full circle (i.e., the starting and ending points overlapped). A full score of 1 was given if the traced pattern was a full circle, otherwise the score was 0. If the maximum deviation of the traced pattern was greater than 5mm from the circumference of the cylinder, the score was 0. Otherwise, the score was 1. Tightness was determined by analyzing how close the trace was to the circumference of the cylinder. A full score of 1 was given if the traced pattern exactly overlapped with the circumference of the cylinder, otherwise the score was 0. The completeness of the circle was analogous to checking if the sealant was applied completely around an object, while the maximum deviation was analogous to cleaning off extra sealant and tightness indicates the efficiency of the sealant application.

All the tasks were performed in a random order using three visual feedback methods, which were provided to the participants randomly. A telescopic mirror with a diameter of 3.25 inches and maximum extension of 29.5 inches was used. A ball joint was located at the intersection of the mirror and the handle, so the mirror could be rotated for omnidirectional viewing. A 5m-long handheld borescope with a 2MP camera at the tip providing a 60° field of view was used for this study. The image was viewed through the manufacturer's application, which was installed on an iPad tablet (Apple). The borescope also had control buttons to zoom in and zoom out of the image on the tablet. An Insta360 One R (Insta360) omnidirectional camera with 5.7k resolution was the omnidirectional camera. The camera image could be viewed through the manufacturer's application, which was installed on an iPad tablet. Moving to the different parts of an omnidirectional image was possible through the touch-screen display on the tablet. The application also had a feature to temporarily zoom through a pinch-out finger gesture, and the image would return back to the initial magnification once the fingers were removed.

The three visibility modalities, mirror, borescope, and omnidirectional camera, were used to view the structures inside the box and perform the tasks, as shown in Figure2, Figure3 and Figure4, respectively. Apart from instructing the participants on how to operate the modalities, they were given sufficient time to explore their use before performing the tasks.

At least one LED had to be externally attached to the mirror and camera to clearly see the structures inside the box, unlike the borescope which had eight in-built light emitting diodes (LED). The participants could view the video stream from the borescope camera through a tablet placed on a cart below the box. Additionally, the participants were given the option of using a wrist mount with the intention of using the borescope while freeing the hand from holding the modality. The omnidirectional camera was fixed on a suction cup that could be placed on the bottom face of the box or mounted on any one of three vertical metal panels placed on the faces of the box, according to the participants' preferences. The participants were allowed to change the location of the camera inside the box throughout the study. Similar to the borescope, the video stream from the camera was displayed on the tablet located below the box.

2.4. Data Analysis

The more time when the arms were overhead and upward flexed neck postures were assumed indicated more postural strain. Videos of task execution were analyzed frame-by-frame using Multimedia Video Task Analysis (MVTA) software (Yen & Radwin, 2000) to quantify the time that upper limb postures were assumed (Dartt et al., 2009). The time during which both arms were above the mid-torso level was classified as "two-arm strain time", and the duration for which the participants looked upwards was classified as "neck strain time". Although all the tasks performed in this study entailed at least one arm above the mid-torso level, the use of the second arm for maneuvering the camera was undesirable.

The screen recordings were also analyzed using MVTA to report how participants used the omnidirectional camera to perform the tasks. For each participant, the recordings were analyzed by dividing the sessions into three categories. If a participant moved or adjusted the position of the camera inside the box during the task, the duration was coded as “camera physical manipulation”. If a participant adjusted the camera viewpoint through the tablet, the duration was coded as “camera viewpoint manipulation”, and if a participant performed one of the three tasks, it was coded as a “manual task”. The segmentation of modality use could only be made for the omnidirectional camera since all three categories occurred simultaneously in the case of the mirror or borescope. The participants physically adjusted both the position and the orientation of the borescope/mirror to change the viewpoint while manipulating objects for the tasks.

Data from the questionnaires (SUS, USE-Ease of Learning, NASA-TLX and Task-wise Modality Preferences), the success ratings and task completion times were analyzed using Python packages to parse the data and generate box and swarm plots, and IBM’s SPSS software (IBM Corp., 2017) was used for the statistical analysis. When distributions were skewed, non-parametric statistical tests were used. The differences between the three modalities were evaluated for each of the values observed (two-arm and neck strain times, task completion times, task success ratings, SUS ratings, USE-Ease of Learning ratings, and NASA-TLX scores) using the within-participants Friedman test and the post-hoc pairwise Wilcoxon Signed-Rank test. The significance threshold was p =.05.

The audio recordings of the semi-structured interviews were manually coded by perusing through the 21 responses. Phrases that highlighted the advantages and disadvantages of each modality were noted to understand the experiences of the participants while using the different modalities for each of the three tasks.

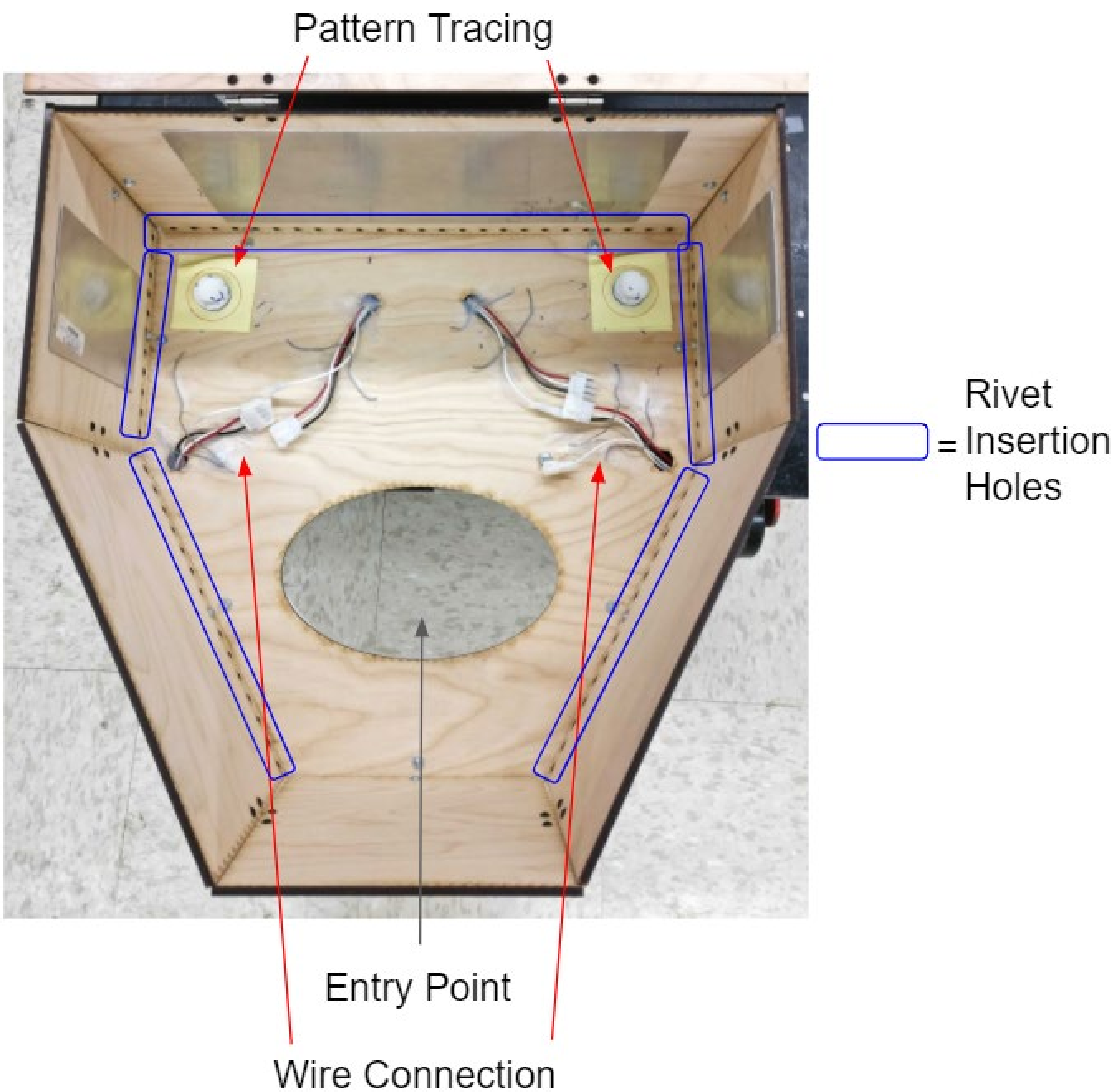


Figure1. Internal structures of the box and the tasks - rivet insertions, wire connection and pattern tracing

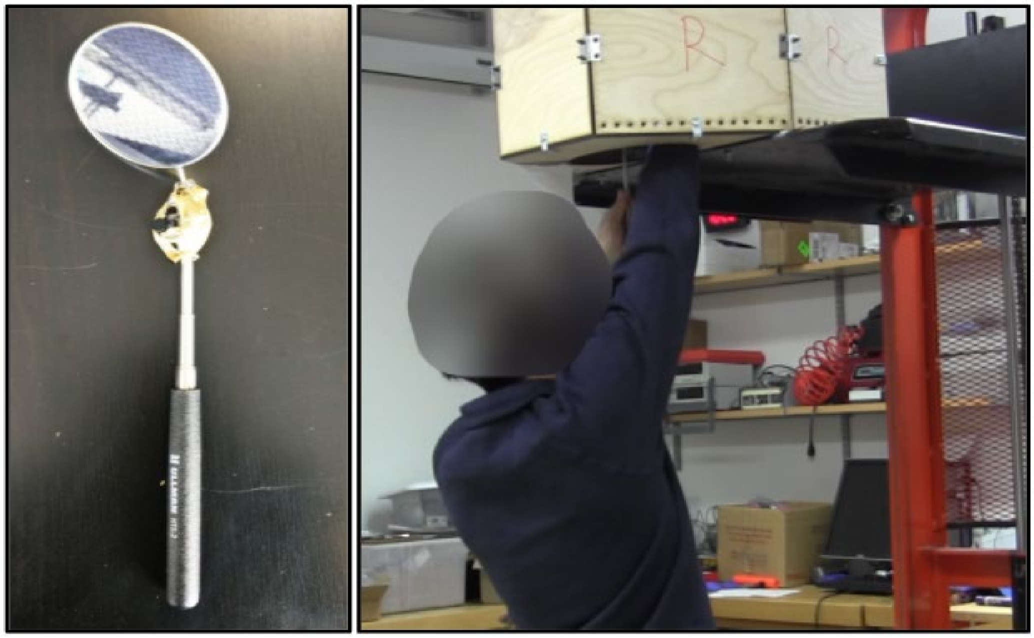


Figure2. Mirror with additional LED light, participant using the mirror for the first rivet insertion task

(a) (b) (c)

Figure 3. (a) Borescope. (b) Participant using the borescope for the second rivet insertion task. (c) A view from the manufacturer's application during the second rivet insertion task showing the yellow rivet inserted into the third hole from the right, as instructed to the participant

(a) (b) (c)

Figure4. (a) Insta360 camera on a suction cup with LED lights. (b) Participant using the omnidirectional camera for the first rivet insertion task. (c) A view from the manufacturer's application during the first rivet insertion task showing the rivet being inserted into the hole.

3. Results

3.1. Time-in-posture

The two-arm and neck strain times are shown in Figure 5. The Friedman test showed significant time differences (χ^2 (2)=18.14, p<.001) between the neck strain time for the three modalities and the pairwise Wilcoxon Signed Rank tests showed that the omnidirectional camera had the least average two-arm strain time compared to the mirror (p<.001) and borescope (p<.001). The omnidirectional camera reduced the average two-arm strain time by more than 2.5 times compared to the mirror and borescope. Further, there was no significant difference between the two-arm strain times for the mirror and the borescope (p=.498). The neck strain time showed significant differences (χ^2 (2)=24.29 ,p<.001) between the modalities. The pairwise post-hoc tests exhibited the least amount of average neck strain time for the omnidirectional camera compared to the mirror (p<.001) and borescope (p=*.014*). Further, there were significant differences observed between the neck strain times of the mirror and the borescope (p<.001). In the case of the mirror, the neck strain time was 83.68% of the total task completion time, while it was only 0.01% and 0.0005% for the borescope and omnidirectional camera, respectively.

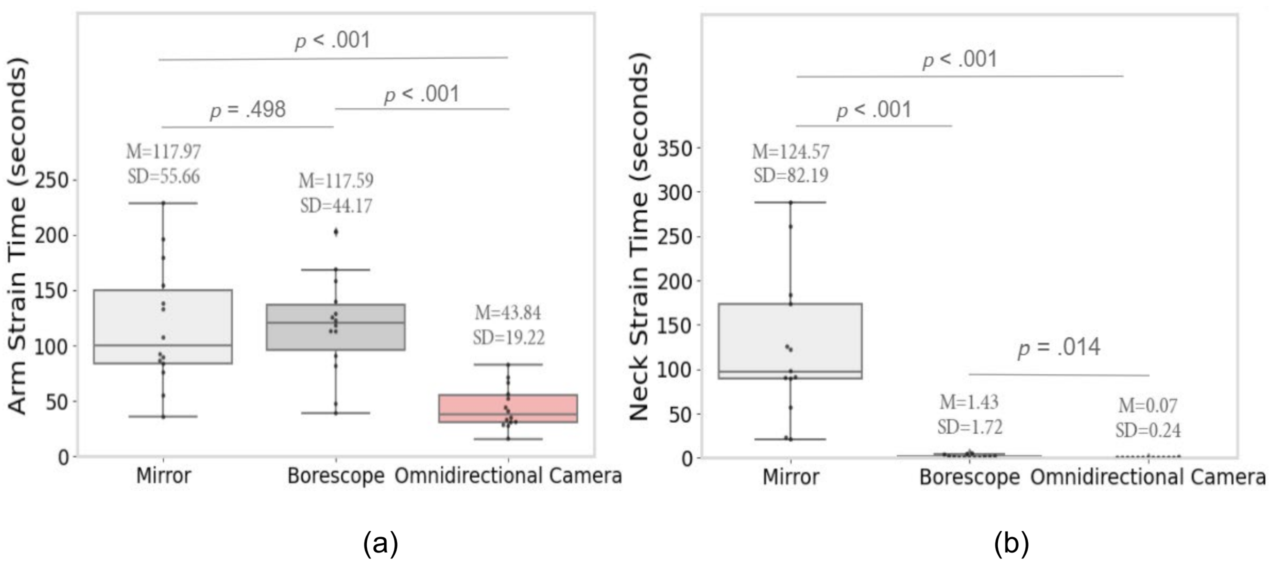


Figure 5: Two-arm (a) and neck strain times (b).

3.2. Task Performance

There were no significant differences (*p*>.05) between the task success ratings for the three modalities (Figure 6). More than 90% of the participants successfully completed the repeated rivet insertion and wire connection tasks with all the modalities. The average scores for the pattern tracing task were not significantly different (*p*>.05) between modalities, although the score for the omnidirectional camera was marginally greater (M=1.33, SD=0.73) compared to the borescope (M=1.1, SD=0.77) and the mirror (M=1.29, SD=0.78).

The completion times for each task, as shown in Figure 7, were not significantly different between the three modalities (*p>.05).* While the omnidirectional camera had shorter task completion times compared to the mirror for the first rivet insertion, the second rivet insertion, and the wire connection tasks, the task completion time for the mirror was marginally less compared to the other modalities for the pattern tracing task.

During the first rivet insertion, wire connection and circle tracing tasks, the camera was located inside the box according to the participants' preference. They could manipulate the camera view to the desired viewpoint through the application and perform the manual operation. In all these cases, the time taken for the manual task was greater than the time taken to place the camera in the box (physical manipulation time) and the time taken to select a correct viewpoint on the application (viewpoint manipulation time), as shown in Figure 8. Additionally, it was observed that 13 participants out of 21 did not physically move the camera inside the box for the second rivet insertion task, which was performed right after the first rivet insertion. Instead, they only used the touchscreen to navigate to the desired viewpoint. This opportunity was solely offered by the omnidirectional camera as it is the only modality that did not require physical maneuvering to change the viewpoint.

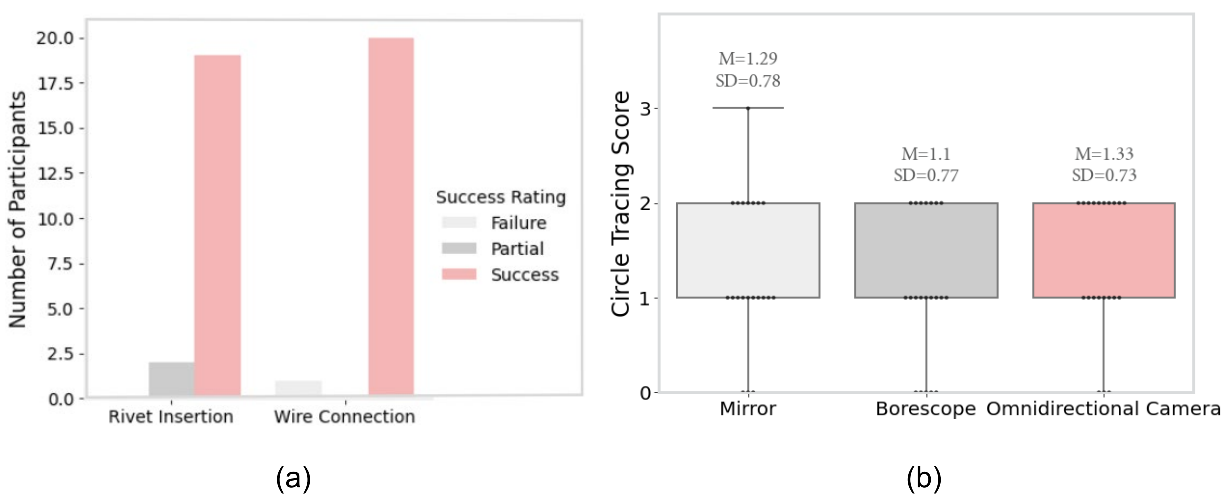


Figure 6. The number of participants who succeeded in the repetitive rivet insertion and wire connection tasks (a) and the circle tracing scores (b).

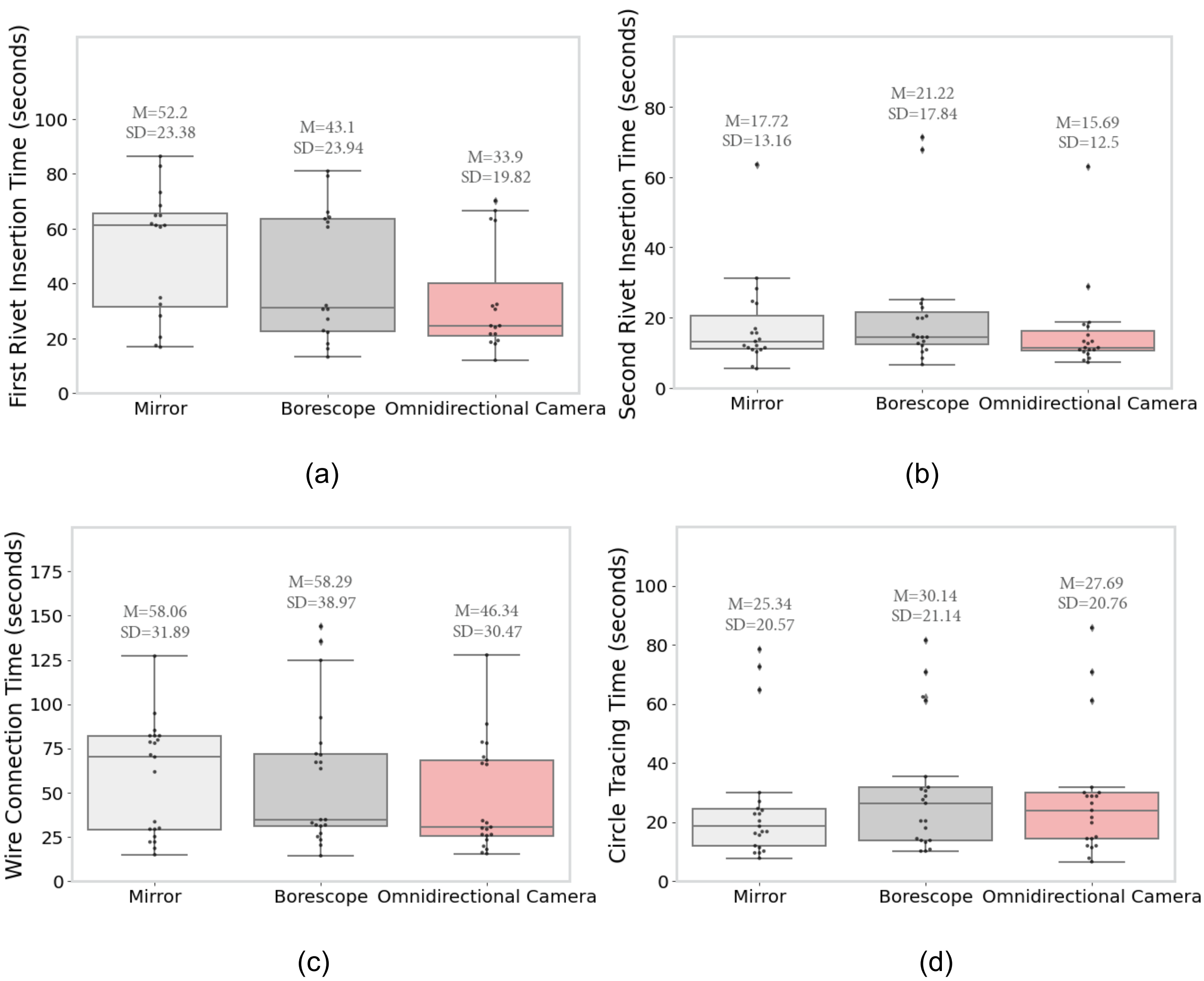


Figure 7. Task completion times for the three modalities in the (a) First rivet insertion task), (b) Second rivet insertion task, (c) Wire connection task, and (d) Circle tracing task.

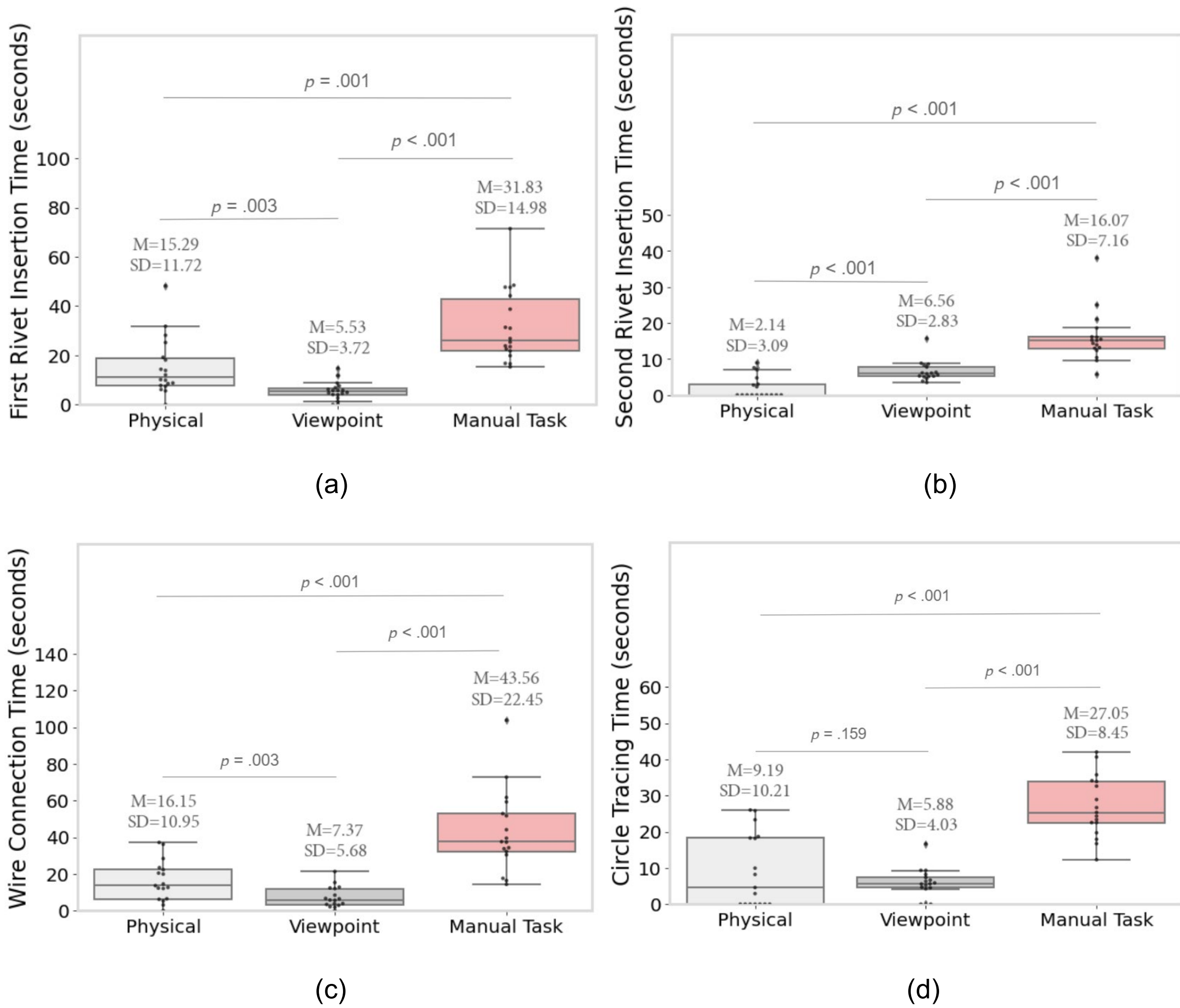


Figure 8. Time taken for the three types of omnidirectional camera usage: (a) First rivet Insertion, (b) Second rivet insertion. (c) Wire connection, and (d) Circle tracing.

3.3. Usability

The SUS-usability scores were significantly different for the three modalities (χ^2 (2)=16.33, *p*<.001), as exhibited by the Friedman test. The pairwise Wilcoxon Signed Rank test showed that the omnidirectional camera scored higher than the mirror (*p*<.001). The test also showed that between the borescope and the omnidirectional camera, the camera scored higher (*p*=.014) and between the mirror and the borescope, the borescope scored higher (*p*=.014), as shown in Figure

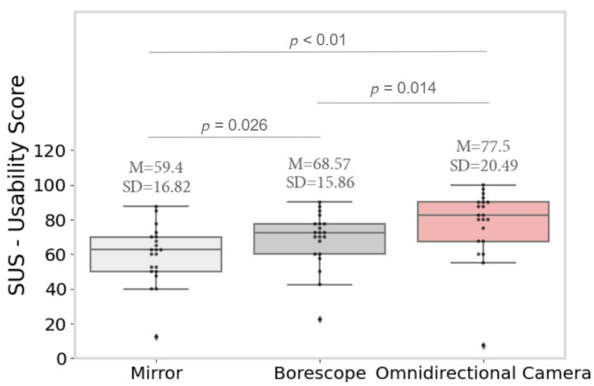
9. Further, the omnidirectional camera scored higher by 13% compared to the borescope, and 30% compared to the mirror.

According to the Friedman test conducted on the USE-ease of learning results, all the modalities scored similarly high (score > 5 out of 7) with no significant differences between the scores (χ^2 (2)=0.98, p>.05), as shown in Figure 9. The Friedman test for the NASA-RTLX scores demonstrated significant differences for the three modalities (χ^2 (2)=12.51, p<.002). Further, the pairwise Wilcoxon Signed Rank tests exhibited significant differences between the RTLX scores of the mirror and the borescope (p=.01), and the omnidirectional camera and the mirror (p=.002). The borescope and the omnidirectional camera scored better by more than 37% compared to the mirror. The pairwise Wilcoxon Signed Rank test also indicated no significant difference between the RTLX scores for the borescope and the camera (p=.347).

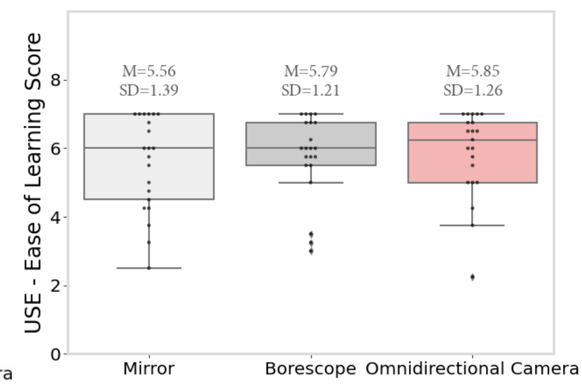
3.4. Participant Feedback

Task-wise modality preferences are shown in Table 1. Seventeen of the 21 participants preferred using the omnidirectional camera for all the three tasks, as purported through the semi-structured interviews. Further, the Task-wise modality preference questionnaire showed that not only did more than half of the participants prefer the omnidirectional camera for all the tasks, but also the camera was preferred by all the participants for the two-handed wire-connection task. This is consistent with the observation that this task required bi-manual manipulation and only the omnidirectional camera can be used while having both hands available to perform the task.

During the semi-structured interviews, the participants reported more advantages for the omnidirectional camera, compared to the other modalities including widest field of view and hands-free use of the modality. Eighteen participants claimed that both the hands could be utilized to perform the manual tasks, if required, by simply placing the camera inside the box once, and then only adjusting the viewpoint through the application before task execution. Additionally, all the participants indicated that the disadvantages of the camera, including image distortion between the two lenses, were trivial, and could be eliminated simply, such as physically rotating the camera. Contrarily, all the participants reported a high level of difficulty while executing two-handed tasks while using the mirror and borescope, since the use of one hand was crucial to maneuver the modality inside the box. The arduousness was exacerbated by the limited field of view offered by these modalities. A common disadvantage shared by all three viewing methods was the obstruction of the viewpoint by the participants' hands, which bolstered task execution through tactile feedback.



(a)



(b)

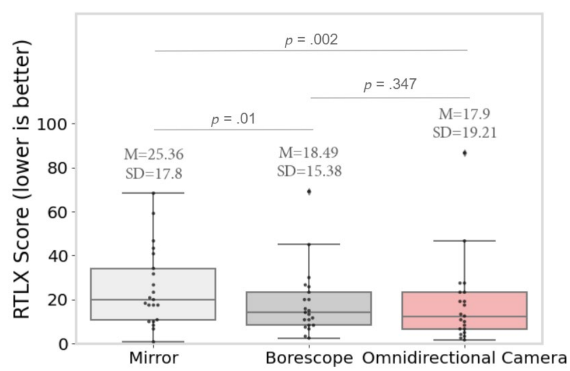


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Figure9. (a) SUS-Usability score for the modalities. (b) USE-Ease of Learning score for the modalities. (c) NASA-RTLX scores for the modalities.

Table 1. Task-wise modality preferences (No. Participants)

Task\Modality	Mirror	Borescope	Omnidirectional Camera
Rivet Insertion	2	8	11
Wire Connection	0	0	21
Circle Tracing	1	5	15

4. Discussion

4.1. Implications

Two of the three tasks in this study (Rivet insertion and Pattern tracing) did not require the use of both the arms to accomplish the tasks. However, in the case of the mirror and the borescope, the participants used both arms while performing these one-handed tasks – one hand to maneuver the modality and the other to perform the task. Stretching both the arms to work overhead is straining (Ray & Teizer, 2012). The omnidirectional camera can reduce bilateral strain, based on the results of this study. While the borescope and the omnidirectional camera facilitated viewing the interior structures of the box through an external display with less neck strain, the mirror entailed upward flexed neck postures to accomplish the tasks. The borescope or the omnidirectional camera were better alternatives for reducing neck strain compared to the mirror for looking into obscured overhead spaces.

Work-related shoulder and neck strain is frequently associated with overhead tasks. Sakakibara et al. (2007) observed arm and head extension during the harvesting of pears and apples among Japanese farmers was related to shoulder and neck disorders. Some interventions include wearable exoskeletons to provide physical assistance during overhead task execution (Greenbaum, 2016). In the current study, rather than a physical intervention, we consdered the benefits of a novel visual method – an omnidirectional camera.

Apart from the two-arm and neck strain times, the other quantitative scores, such as the SUS and NASA-TLX scores, indicate that not only was usability of the omnidirectional camera better, but also that the borescope and the omnidirectional camera required less workload than the mirror. The USE scores suggest that learning the use of an omnidirectional camera is as easy as learning how to use a mirror or a borescope. Additionally, the participants' positive opinions about the omnidirectional camera, including hands-free visual access and wide field of view, bolster the greater usability of the visual method compared to the other modalities, specifically for two-handed tasks. As observed by Mukai et al. (2020) while studying the use of omnidirectional cameras in laparoscopic surgeries, the flexibility to view an image without having to physically move the camera can be useful to accomplish tasks in limited visibility spaces.

An unexpected trend in the task completion time was observed for the pattern tracing task. From the video recordings, the marginally lower task completion time for the mirror might be due to participants forgoing the use of the mirror to execute the task, simply replying on tactile feedback to locate relevant locations. Though the intention of the tasks used for this study was to simulate aviation assembly operations under controlled conditions, a possible explanation for the absence of differences in successes and task completion times between the modalities was the less challenging nature of the simulated tasks in comparison to the actual manufacturing activities. Perhaps, the lack of task difficulty and the short duration of the tasks assisted in the successful completion of all the tasks by most of the participants at approximately the same times.

4.2. Limitations and Future Work

Overall, the results of this study indicate that the omnidirectional camera can reduce postural strain while providing better usability compared to the conventionally used visual methods (mirror and borescope) during task execution in overhead and obscure spaces. Since this laboratory study involved simulated tasks, the long-term benefits of incorporating the use of an omnidirectional camera by aircraft manufacturing workers in such spaces need to be evaluated.

Although most of the results of this study support the omnidirectional camera, ascertaining how the outcomes apply to the real-world still needs to be established. There are important differences in the level of work experience between the subjects of this study and the aerospace manufacturing workers. Furthermore, the tasks were of short duration and executed in a lab setting. Therefore, as a future work, we are planning to replicate this study in an aerospace manufacturing setting with the operators performing real tasks.

Based on the video analysis, most of the participants physically placed the omnidirectional camera in the box before inserting the first rivet and inserted the second rivet by only changing the viewpoint and maintaining the same camera position in the box. It is anticipated that for highly repetitive tasks, an omnidirectional camera could be placed in the workspace once, with further viewpoint updates made to adapt to each repetition of the task. This could allow workers to view the task with limited additional time cost for repetitions. Since our study focused on single (or dual) tasks, we cannot confirm this. Future work will explore repeated tasks and autonomous viewpoint selection within the omnidirectional video feed.

While the study allowed participants to position the omnidirectional camera inside the box according to their preferences, most of the participants expressed difficulty in obtaining the perfect viewing angle of the structure pertaining to each task. To address this issue, the next phase of this research is to explore if autonomous detection of optimal viewpoint(s) can solve this issue while the camera is positioned at the center of the limited feedback setting. These visual aids could be viewed through wearable technologies like Google glasses (Google) or Microsoft's Hololens (Microsoft) to enhance the visualization experience for the aviation manufacturing operators.

5. Highlights

- The omnidirectional camera had shorter two-arm and neck strain times than the mirror and borescope.
- The omnidirectional camera had better usability compared to the mirror and borescope.
- No significant differences between modality task completion times were observed.

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