A Maintenance Domain Experiment of Efficiency, and Precision Comparing Augmented Reality and Traditionally Cued Procedures

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ABSTRACT

Combat lethality depends on viable and repeatable maintenance processes. Technological advances have increased the complexity of maintenance communication. The technical manual, while essential, is not the optimal communication medium for all types of information. Augmented reality (AR), which is the overlaying of contextual computer-generated information upon the real world, is a candidate to mitigate complexity because intuitively AR appears to provide a better method of communication. Yet little is known about the efficiency, precision, and variability of AR compared to traditional methods. This research studied the effect of augmented reality cued (ARC) maintenance procedures on human efficiency and precision. Participants performed two sets of tasks in two conditions, one AR and one traditional (control), enabling a pairwise comparison. The first task set directed participants to place simple "erector-set"-like parts in specific locations and the second task set used such parts to construct a more complex object. In the control condition, participants used a technical manual. In the AR condition, an AR head mounted display presented the same information in a visual form. The AR condition consisted of virtual guides projected in real 3D space via a Microsoft HoloLens. Instructions in both task sets guided participants through decomposed maintenance procedures that induced absolute, cumulative, absolute referential, and complexity errors. Results indicate that the assembly procedure is statistically more efficient and precise within the AR condition. ARC placement actions of small parts are statistically more efficient and generally at least as precise.

ABOUT THE AUTHORS

CDR Christopher Angelopoulos commissioned as a naval officer at University of Florida with a bachelor's degree in computer engineering in 1994. Various operational F/A-18 tours supported global international and joint operations over the next 14 years. He served the NIOC Norfolk Cyber Readiness director in charge of red and blue team operations which included OPERATION ROLLING TIDE. As the first Air Operations Officer for PCU Gerald R. Ford (CVN 78), he created a Mixed Reality Innovation Center generating interest from the Office of Naval Research, SPAWAR, and NAWC/TSD. He earned a master's degree in Modeling, Virtual Environment, and Simulation at the Naval Postgraduate School and received the highest academic award across campus. He is now faculty at NPS.

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Perry McDowell attended nuclear power training after commissioning as a naval officer. He served in USS VIRGINIA (CGN-38) as M-division officer, R-division officer, and DCA from 1990-1993. He later served as operations officer in USS ELROD (FFG-55) from 1996-1997 and reactors control assistant and main propulsion assistant in USS ENTERPRISE (CVN-65) from 1997-2000. In 1995, Perry earned a Master's of Science degree in computer science at the Naval Postgraduate School, where he was awarded the Grace Murray Hopper Award as outstanding computer science student. Upon leaving the Navy in 2000, he returned to NPS and joined the faculty. Although he has served as a principle investigator for a wide variety of projects in the MOVES Institute, from 2003 – 2012 he worked primarily as the Executive Director for the Delta3D open source game engine. From 2012 to the present, he has taught courses in simulation for training and conducted research in the areas of training effectiveness and the creation of systems to improve warfighter performance.

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INTRODUCTION

Materiel readiness is a critical supporting pillar to combat lethality. Failed maintenance actions divert essential resources, increase risk to mission accomplishment, and ultimately diminish combat lethality. Addressing time on task and first-time quality and variability of maintenance performance frees resources, adds stability to maintenance processes and injects predictability into logistic operations. Augmented reality (AR) cued maintenance procedures have the potential to significantly alter the status quo of maintenance actions by reducing the time on task and variability of performance while simultaneously increasing first time quality.

There are many types of errors inherent in performing maintenance. One of the most prevalent contributing factors to these errors is a failure to correctly communicate information to the performer. Technical manuals used today typically present information in textual or graphical form. This requires the engineer to present information and procedures, many of which are dynamic and three dimensional, within the constraints of a static two-dimensional manual. Translating engineering processes and procedures into a technical manual can induce unintended error on the front end, while the manual's end user can also easily misinterpret the translation on the back end. Assumptions of the technical competency of the performer are baked into the manual which, if incorrect, can decrease procedural compliance. While written instructions are useful in the absence of a better alternative, they are unable to support current technological complexity at both a sustainable cost and acceptable maintenance action failure rate.

Fundamentally, AR alters the communication pathway that connects designers of things to those people who fix them (i.e. maintenance professionals). It brings information to the user in real-time, in context and reactive to the real world. By expanding the scope of presentation AR can keep spatial tasks spatial.

Many are predicting that AR will significantly benefit maintenance and manufacturing (Abraham & Annunziata, 2017) (Robinson, 2017). Currently, several companies, including large defense contractors, are investigating AR to improve these areas ("Boeing Tests Augmented Reality in the Factory," 2018) ("GE Aviation Successfully Augmented Reality in Maintenance," 2017). Our research shows that AR has significant advantages in efficiency, which we define as a combination of precision and time. There was no significant generalized advantage in precision for either condition. AR appears to substantially reduce variation of both time and precision.

This experiment seeks to answer the question: To what extent does augmented reality cueing affect efficiency, precision, and variability of basic maintenance tasks as compared to written forms of communication (e.g., technical publications)? (Angelopoulos, 2018)

Angelopoulos (2018) is the source for any reprinted information in this paper. Readers interested in the full thesis will find it here: https://calhoun.nps.edu/handle/10945/58537.

AR Defined

Augmented reality, for the purposes of this research, is best defined by Milgram, Takemura, Utsumi, and Kishino (1994) who categorized AR as "augmenting natural feedback to the operator with simulated cues" (p. 284) and Azuma (1997) who asserted three conditions are necessary for a system to be considered AR: "combines real and virtual, interactive in real time, registered in 3-D" (p. 2).

Figure 1 depicts the usefulness of the different communication mediums coupled to their primary operating environments. As a generalized statement, today manuals document our maintenance procedures. Manuals are used to train the end user and localize the necessary procedural information near the work environment. The manuals are unable to integrate information with the work element seamlessly. AR alters this dynamic with the potential to support real-time operations as well as post-work performance evaluation and quality assurance. AR's ability to capture and transport objective measures enables assessment in the post-work environment.

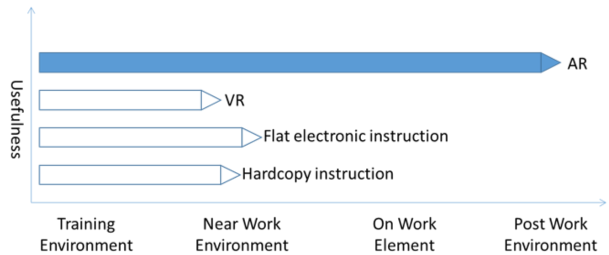

Figure 1. AR VR and Technical Manual Usefulness Comparison. Source Angelopoulos (2018)

Similar Research

Tang, Owen, Biocca, and Mou (2003) evaluated 75 university students after Duplo block assembly for precision and completion time with information presented via four mediums including AR. The authors concluded that the printed manual is significantly slower and AR is significantly more precise than all other conditions. Of note: Duplo blocks can only connect in a finite number of ways limiting the granularity of the precision metric. Henderson and Feiner (2011) conducted a comparative AR study of military mechanics between text-based instruction and a head mounted display concluding AR directed gaze on task is faster than flat panel cueing. Both articles highlighted the need to expose a more fundamental understanding of why AR is different than other methods of communication with respect to maintenance tasks. In doing so, future work can more readily generalize AR benefits to each specific job based on a categorization of human actions proven to be conducive to AR use.

METHODOLOGY

This research compared the completion time and precision of workers performing similar tasks with instructions using manuals and AR cueing. We combined these two parameters (completion time and precision) into a third which we called "efficiency." Participants performed two types of jobs which were generic versions of tasks that workers often perform: placing objects at a given distance from a reference point and constructing complex objects from a set of parts. Each participant performed five tasks. The first four tasks entailed placing erector set pieces on a paper following instructions if followed correctly would result in their proper placement of the pieces in specific locations and specific orientations. The fifth task called for building a complex object from multiple erector set pieces and a wire. Figure 2 depicts the experiment apparatus.

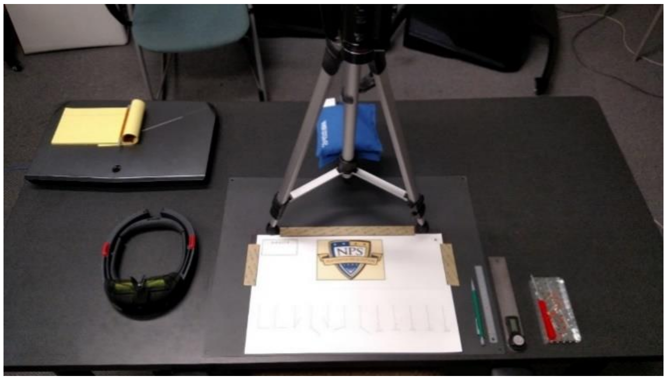

Figure 2. Experiment Apparatus

We examined four types of errors in our study: absolute error, absolute referential error, cumulative error, and complexity error. We defined absolute error as a distance from a known fixed physical reference. Absolute referential error is the total error (absolute) made when taking into account multiple different distances from a known fixed physical reference. Cumulative error is additive error produced after making several placements or measurements. Complexity errors are mistakes in the final location and/or composition of objects which require several complex steps to place or build the objects.

One condition presented the participant with information formatted similarly to a traditional technical manual via text, diagrams, and images, which we referred to as "traditionally cued" (TC). The quality of the traditional method to deliver information via technical manuals varies between disciplines and manuals. Some manuals are easy to use, with straightforward procedures and sufficient illustrations to adequately demonstrate tasks. In order to ensure that we did not handicap the TC condition, we modeled the technical manual the participants used on the best of the breed and included more images than normally found in manuals. Figure 3 is representative of the control condition with the entire manual included in (Angelopoulos, 2018). In this condition, participants used a ruler and digital protractor to place pieces according to the directions in the manual. The AR condition presented information to the participant through an augmented reality helmet mounted display, the Microsoft HoloLens, and we referred to this as the "augmented reality cued" (ARC) condition. In this condition, the HoloLens displayed 2D and 3D objects virtually as well as instructions for the tasks. All participants completed tasks within both conditions. We counterbalanced the experiment, randomly choosing half the participants to first conduct the tasks using traditional guidance and then perform the tasks using ARC. The other half performed the same tasks in the reverse order. A video camera recorded participants performing the tasks under both conditions. We examined the video to determine completion times, distance measurements, and correctness to produce human efficiency and precision data for each condition. This design enabled a pairwise comparison between participants' performance under each condition.

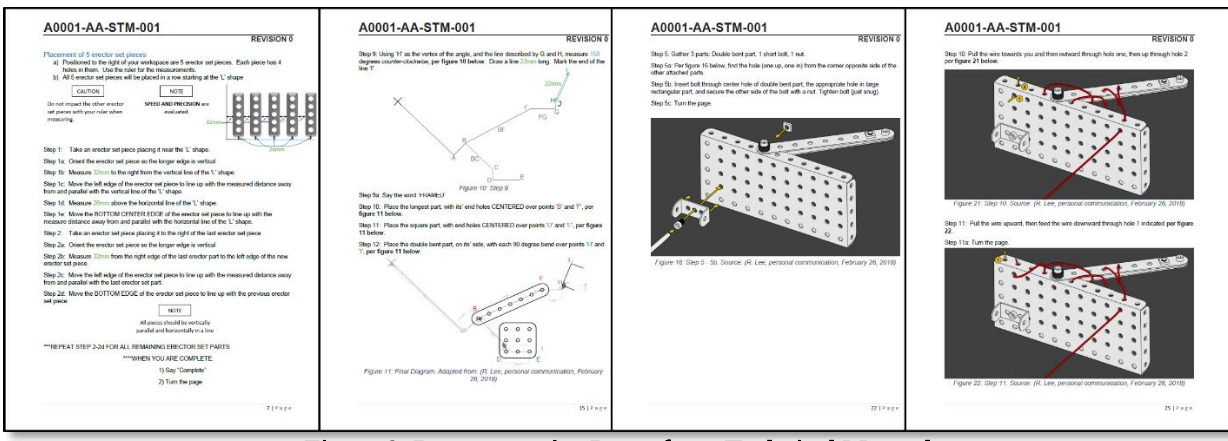
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Figure 3. Representative Pages from Technical Manual

While performing tasks 1-4 in the ARC condition, subjects looked at the paper with the with NPS logo as a fiducial marker*. Wireframe representations of the objects appeared in the HoloLens in the proper position on the paper, and subjects placed the real object as close to the virtual object as possible. While performing task 5, the HoloLens displayed the instructions for a given step of the task, and the step was performed on the virtual object by invisible hands. For example, if the step was to insert a bolt into a given hole on a piece and secure it with a nut, the piece was shown, the screw would fly into the correct position through the hole, and the nut would screw itself onto the bolt. The completed object would then remain in the HoloLens to act as an exemplar for the subject to refer to. Figure 4 is a composite image showing one of the experimenters wearing a HoloLens and showing the virtual objects he is seeing overlaid on the real world. He is building the object in his hands, while the HoloLens displays the virtual object for him to reference in the bottom-middle of the image.

Figure 4. Representative Image from Augmented Reality Condition†

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* A fiducial marker is an object which an AR device uses to position itself and virtual objects in the real world.

† Source (R. Lee, personal communication, May 2018)

Participants

Thirty-four enlisted Marine aviation maintenance personnel volunteered as participants in the experiment (29 males, 5 females). No compensation was offered for participation. Maintenance experience, both on and off the job, ranged from zero (new accessions) to 21 years. Military maintenance experience ranged from zero to 16 years. Computer gaming experience ranged from zero to 30 hours per week.

The Experiment

The experiment began with participants training in one condition until each felt confident to work without prompting. Training for the TC condition centered around ruler and protractor use, while training for the ARC condition focused on the user interface of the HoloLens. Participants conducted all five tasks under one condition. After completing these, participants underwent training for the other condition, and then repeated the five tasks using the other condition. Five tasks elicited four different errors. These errors affected completion time, distance from known perfect position, or both. Under both conditions, the participants completed the tasks on a piece of 11" x 17" paper, which was usable to mark on as necessary. The top half had a block for participant number and the NPS logo, which served as the virtual to real world reference for the HoloLens, while the bottom half varied with the task. Between each task, the experimenter changed the paper.

For task 1, the paper had five identical L-shapes, and the participants had to place 5 identical erector set pieces a given horizontal and vertical distance from the 5 identical L-shapes. Measuring horizontal and vertical distance each once, then placing the part determined absolute error. Figure 5 shows the desired outcome after the participant has correctly placed the erector set pieces.

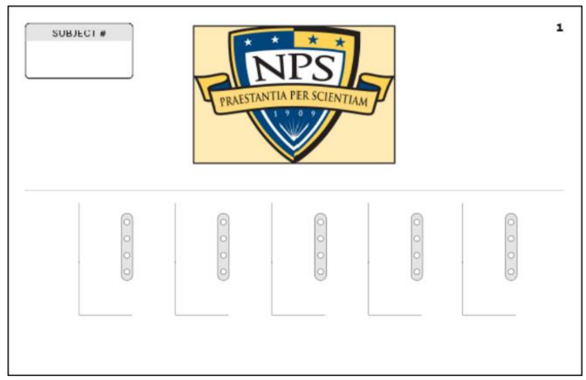

Figure 5. End State Task 1

For task 2, the workspace had one L-shape near the left side. This task required participants to place 5 identical erector set pieces. All participants measured a given distance vertically above the L-shape's lower leg. For horizontal placement, the provided distance began from the L-shape's vertical leg, and each subsequent placement was this same distance from the piece immediately to its left. This forced participants to measure from the previously placed part producing a cumulative error. Figure 6 shows the desired outcome after the participant has correctly placed the erector set pieces.

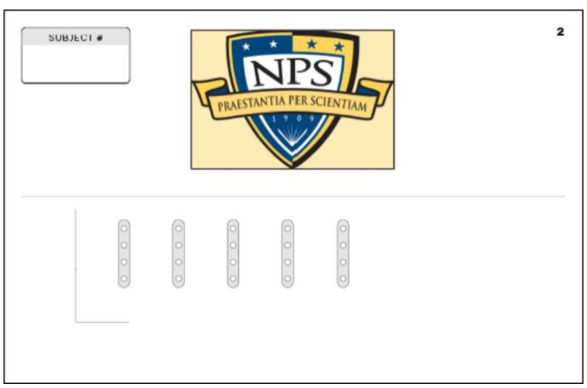

Figure 6. End State Task 2

Task 3 required participants to place 5 identical erector set parts within 5 L shapes, similar to task one. However, in this case, the position of each piece from its L-shape was a different horizontal and vertical value. This task's design forced participants to memorize distances or continually return to the manual to gather new information inducing absolute referential error. Figure 7 shows the desired outcome after the participant has correctly placed the erector set pieces.

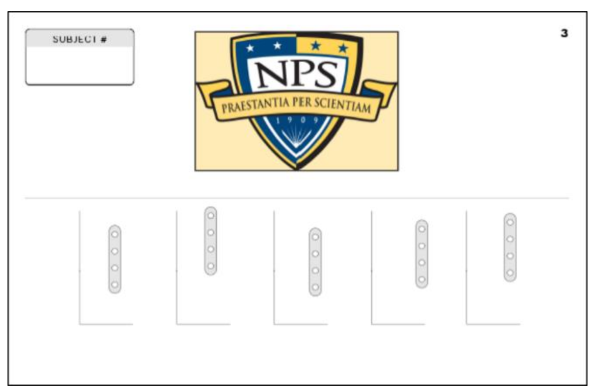

Figure 7. End State Task 3

Task 4 required participants to place three different erector-set parts into the workspace in a non-intuitive pattern. The TC condition directed participants to start at the "X" on the left side of the paper and draw a structure to facilitate part placement. After drawing the structure, instructions directed

Figure 8. End State Task 4

participants to place three pieces at certain specific locations. In the ARC condition, the HoloLens displayed a virtual version of each object in its correct location. This task is a primary comparison for each condition's ability to communicate a complex placement action. In doing so, the task elicits complexity (placement) error. The second image from the left of Figure 3 depicts two steps of this task under the TC condition, while Figure 8 shows the desired end state.

Task 5 was an assembly procedure of a single wire and multiple erector set parts. This task is analogous to a procedure expected of a maintenance professional. In both conditions, the object was comprised of a wire, one large 3D rectangular erector-set box with one open side, two long erector-set parts, one erector C part, two small short bolts, one small long bolt, one small thick plastic washer, and two small metal washers. The final constructed objects were different for each condition, to minimize transfer of training. Potential errors were any deviation from the correct construction and each component could have multiple errors. For example, bolts required placement into the correct hole (potential error #1), in the correct direction (potential error #2), while the wire had to go through the correct hole (potential error #1), in the correct direction (potential error #2), and wind either clockwise or counterclockwise (potential error #3). Each of the objects had similar numbers of potential errors – fifty-four for the AR item, 52 for the traditionally guided item. The last two images of Figure 3 are three steps for this task within the technical manual condition while Figure 4 shows the AR condition. Figure 9 depicts the end states of the objects for each condition.

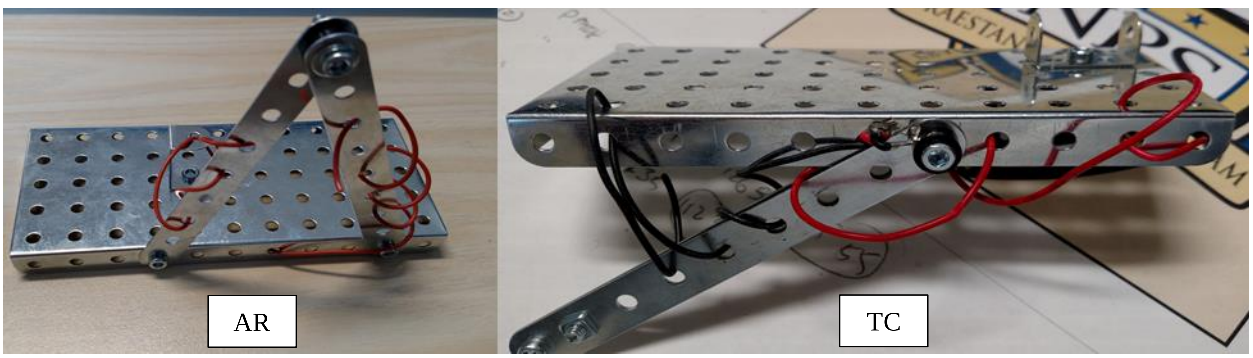

Figure 9. Completed Objects for Task 5 for AR and TC Conditions

Data Extraction

After the completion of the experiment, we examined the video recordings to extract data on the participants' performance. We recorded the time to complete each task, as well as measuring the distance of the objects from their perfect positions. Continuous video feeds ensured precise data extraction. Timing data was granular to the $1/30^{th}$ of a second, while distance data was granular to 0.1mm. These measurements facilitated the production of efficiency and precision data.

Completion Time

In all tasks except task 4, timing began when each participant verbally stated "Begin" (ARC) or turned the page in the manual (TC) and ended with the disengagement of the final touch of the last part. Task 4 broke the timing into a "total completion time" and a "placement-only time." In task 4 under the TC condition, participants formed a complex diagram on the workspace using a ruler and a protractor and then placed the parts upon specific points within the diagram. The last mark of constructing the diagram in the workspace started the placement-only clock. The last touch of the last part marked the end of both clocks. The augmented reality cued condition guided participant to direct placement and therefore both placement-only and total completion times were the same.

Image Correction

When conducting distance measurements from images, we had to account for two issues. The first of these, non-orthogonality, occurs if the camera lens axis is not orthogonal to the captured surface. This causes distorted distances other than at the image center, requiring adjustment to produce accurate measurements of the detail required. A series of linear image alterations within Adobe Photoshop® corrected non-orthogonal image capture. Second, even though the camera did not use a fisheye lens, all lenses have a fisheye effect which skews distances outside the center of the image. A fisheye tool within Adobe After Effects® corrected this lens distortion. Angelopoulos (2018) contains amplification and validation of the correction process.

Precision Data

Analysis of corrected images captured from participant video data yielded meaningful distance data. We compared this distance to a known perfect position to determine error for each task. In general, aggregation of all horizontal and vertical error produced precision data for each task.[‡] To validate our precision measure, five people who were not part of the experiment completed a visual ranking of 5 placed parts in order from best to worst precision given our definition stated above. Their ranking agreed with the precision algorithm.[§]

Task 5, the assembly procedure, differs from the aforementioned precision data process by identifying correct placement of parts and routing of wire through the constructed object. Normalizing these values facilitated proper comparison.

Efficiency Data

We considered efficiency as “correct work at a cost”. The analog for correct work was precision, represented as error from a known perfect position. Completion time was the cost. Efficiency must differentiate between two participants that complete a task in the same amount of time recognizing the one with less error as better. Of equal importance, is to correctly evaluate the quicker participant who has the same precision as better. Furthermore, two participants are equally performing when one participant is quick but less precise and the other is slow but more precise. A simple algorithm of precision (error in mm) multiplied by completion time (seconds) is a rough but adequate representation of the aforementioned conditions. This is by design a general representation giving no preference for completion time or precision, while also not altering the efficiency equation for maximum completion times or minimum precision requirements dictated by a specific job requirement. Smaller efficiency values are better.

Experimental Error

An assortment of factors injected unwanted errors into the experimental process: two cameras, two experimental stations, and pixilation. Two different cameras with the same resolution gathered video data. Each camera had its own image correction procedure to help mitigate the variance. Two experimental stations enabled parallel operation effectively doubling throughput, which necessitated another investigator. A script read to each participant minimized variability between the stations while pre-experiment training sessions harmonized procedures. While distance measurements were to the 0.1mm, pixilation of the image required the investigators to estimate the best pixel to choose to bound the measurement.

Calibration

Microsoft HoloLens is currently in development with an optimal working distance at roughly two meters (“Hologram stability,” n.d.). The calibration process adjusts image placement in each display for the individual’s interpupillary distance (IPD). This process appears to be less precise when lined up with 0.1mm measurements. It was apparent that calibration error induced positional error into the experiment. No analysis assessed the variability. Reducing or eliminating IPD estimation error will only improve precision within any AR head mounted display calibrating via IPD estimation.

RESULTS

ARC data for one participant was lost and therefore that participant was removed from all comparisons. Histogram analysis for each task within each condition exposed few outlier data points (outside 3IQR). Angelopoulos (2018) contains histograms which include and exclude the outliers. Data reported here excludes the outliers.

[‡] Angelopoulos (2018) provides a complete description of the procedure for each task.
[§] Angelopoulos (2018), Appendix D, depicts the ranked parts.

Efficiency

The aforementioned algorithm based on completion times (seconds) and precision (millimeters) data produced meaningful efficiency data. Table 1 is the result of a pairwise comparison between ARC and TC efficiency data and depicts advantages ARC procedures have over technical manuals with respect to small parts placement, assembly, and wiring tasks.

Table 1. Efficiency Statistics. Source Angelopoulos (2018)

	Error Type	*95% Confidence Interval*		*P Value*	*Condition Advantage*
Task 1	Absolute	4313.24	10432.18	<0.0001	ARC
Task 2	Cumulative	3197.59	9930.9	<0.0001	ARC
Task 3	Absolute Referential	3009.2	5507.2	<0.0001	ARC
Task 4	Complexity (Placement – Completion Time)	34676.28	40540.03	<0.0001	ARC
Task 4	Complexity (Placement Only Time)	1072.81	2863.63	<0.0001	ARC
Task 5	Complexity (Assembly)	8.264	166.15	0.0315	ARC

Precision

Distances extracted from corrected images compared to known perfect positioning produced precision data. Table 2 is the result of a pairwise comparison between ARC and TC conditions summarizing precision advantages based on the type of error.

Table 2. Precision Statistics. Source Angelopoulos (2018)

	Error Type	*95% Confidence Interval*		*P Value*	*Condition Advantage*
Task 1	Absolute	-20.22	5.47	0.249	Neither
Task 2	Cumulative	-0.12	34.2	0.0648	Neither
Task 3	Absolute Referential	-23.99	-4.427	0.0058	TC
Task 4	Complexity (Placement)	-4.43	16.06	0.2557	Neither
Task 5	Complexity (Assembly)	0.01	0.029	<0.0001	ARC

Technical manuals elicit statistically less positional error for small part placement vice augmented reality. Tasks that present absolute or complexity error for small part placement show no significant difference, while cumulative error tasks trend strongly in favor of augmented reality. Complexity (assembly) tasks most analogous to repair and build maintenance actions are statistically more precise within augmented reality when using small parts and wiring.

AR and Technical Manual Variation within Tasks

Table 3 depicts standard deviation from the mean for each task and condition. This comparison represents the predictability of individual maintenance actions and associated percent improvement. AR considerably reduces the variability for completion times as well as the associated variability for precision.

Table 3. Variation in Standard Deviation Between Conditions

	AR	*Technical Manual*	*Advantage*	*% Improvement*
Task 1				
Completion Time	15.67 secs	176.7 secs	AR	91.13
Precision	14.68	46.06	AR	68.12
Task 2				
Completion Time	14.36 secs	157.65 secs	AR	90.89
Precision	3.06	41.44	AR	92.62
Task 3				
Completion Time	12.83 secs	149.83 secs	AR	91.43
Precision	14.9	22.22	AR	32.94
Task 4				
Completion Time	18.7 secs	291.05 secs	AR	93.57
Precision	16.43	27.57	AR	40.41
Task 4				
Placement Time	18.7 secs	30.37 secs	AR	38.42
Task 5				
Completion Time	167.38 secs	185.25 secs	AR	9.65
Precision	0.0126	0.026	AR	51.54

DISCUSSION OF RESULTS

This experiment compared performing tasks following the guidance in technical manuals to performing the same tasks where the guidance is delivered via AR. We obtained three major findings from the results. The first is that using AR produces results that are far more efficient than using traditional methods. This finding is the most important. For all the tasks we examined, AR was significantly more efficient, which demonstrates that AR indeed delivers the benefits many expect it to. Since we examined very basic, almost atomic tasks, it indicates that AR's advantages are intrinsic and not just the fortunate result of choosing a more complex task that happened to work well in AR. Additionally, we purposefully made the technical manual better than those normally used, so the result would likely be more pronounced in normal maintenance operations.

The second finding is that the precision results did not offer a general decisive advantage to one condition. TC produced better results for task 3, which measured absolute referential error. In the ARC condition, there was little difference in the participants' actions between tasks 1 and 3 – in both, they just had to place the object where the overlay indicated. However, in the TC condition, task 3 was a more demanding task since the distances changed for each of the five objects, while the distances had remained the same in task 1. As discussed earlier, the HoloLens has inherent positional error due to the apparent roughness of the calibration procedure to account for differences in interpupillary distances, especially at distances less than 2 meters. A better AR display, specifically designed for work within an arm's length and with a more detailed calibration procedure, would likely overlay the virtual objects more precisely in the real world, which would increase the precision of users.

The third finding is that ARC produced far less variability in both the time to complete tasks and the corresponding precision. This has far reaching consequences. If this reduction in variance applies to most other maintenance actions, it could make the ability and experience levels of the individual performing maintenance less important. This finding can have significant impact on maintenance force accessions and training.

Another interesting result is the variation of task 5 (assembly). All tasks within the experiment presented significant improvements in variation for completion time and precision. On the other hand, task 5 does not appear to reduce the time variation of the same magnitude as the other tasks. We attribute this primarily to the construction of the technical manual where the intent was to present information the best possible way. We believe a realistic technical manual would not simplify each step to this level and would use less images. This result alone implies that images of 3D (spatial) tasks communicate better than text and AR communicates better than images.

APPLICATIONS OF THIS RESEARCH

This research has provided strong evidence that AR produces significant improvements in efficiency and reductions in variation when performing basic maintenance tasks. We view it as an early step in classifying the types of tasks where using AR greatly improves performance and those where it does not. By decomposing more complex tasks into their more basic subtasks, it may be possible to accurately predict the effects of using AR for an advanced task prior to building and testing the system.

Variability represents a metric to help evaluate the efficacy of communication between the designer and the maintenance professional. High variability may indicate that there is difficulty in communicating the creator's intent to the maintenance technician. In production environments, large variance in performance creates a lack of predictability which can adversely affect several aspects of production. The ramifications impact the entire process from part acquisition to installation and even quality assurance. Insertion of stability in any portion of the logistic tail translates to more effective use of manpower, money, and time. This research indicates that AR can reduce this variability.

CONCLUSION

Our research seeks add to the baseline knowledge of AR within the maintenance domain when dealing with small part placement, wiring and assembly. Angelopoulos (2018) hypothesized that AR cued maintenance actions are statistically different in efficiency and precision when compared to a technical manual. Thirty-four Marine maintenance professionals, through experimentation, showed the statistical advantage AR has over a technical manual when evaluated for efficiency of small part placement coupled to a generally equal precision. For assembly using small parts or wiring, AR is statistically more advantageous in both efficiency and precision.

DoD and industry expend significant resources to ensure acceptable materiel condition of assets. While failed maintenance actions' effects to industry ranges from financial to loss of life, in the DoD these reduce combat lethality, and ultimately national security. For these reasons, scientific rigor must baseline DoD leadership decisions on how to effectively leverage or disregard technological advances. This research confirms the intuition of many that AR produces tangible benefits to maintenance performance.

ACKNOWLEDGEMENTS

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