ARL-TR-8924 ● MAR 2020

Space Perception in Augmented Reality: Emerging Recommendations for Tailoring Distance Cues to Virtual Content in Augmented-Reality Applications

by Michael Geuss, Jonathan Bakdash, Shannon Moore, Laura Marusich, Eric Holder, and Joe Campanelli

NOTICES

Disclaimers

ARL-TR-8924 ● Mar 2020

Space Perception in Augmented Reality: Emerging Recommendations for Tailoring Distance Cues to Virtual Content in Augmented-Reality Applications

Michael Geuss, Jonathan Bakdash, Shannon Moore, Laura Marusich, Eric Holder, and Joe Campanelli
Human Research and Engineering Directorate, CCDC Army Research Laboratory

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
March 2020	Technical Report	December 2019 – February 2020

4. TITLE AND SUBTITLE Space Perception in Augmented Reality: Emerging Recommendations for Tailoring Distance Cues to Virtual Content in Augmented-Reality Applications	**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Michael Geuss, Jonathan Bakdash, Shannon Moore, Laura Marusich, and Eric Holder	**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) CCDC Army Research Laboratory ATTN: FCDD-RLH-FC Aberdeen Proving Ground, MD 21005-5425	**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-TR-8924
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)** **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
ORCID ID(s): Michael Geuss, 0000-0002-2611-7544; Jonathan Bakdash, 0000-0002-1409-4779; Shannon Moore, 0000-0002-4986-1659; Laura Marusich, 0000-0002-3524-6110; Eric Holder, 0000-0002-4408-7465; Joe Campanelli, 0000-0002-5470-0382

14. ABSTRACT
Augmented-reality (AR) displays render virtual content overlaid on the real world. AR offers great potential for Soldiers to immediately perceive relevant tactical information without the need to consult a physical map or other reference material, or divert their eyes away from the immediate environment. However, realizing the potential benefits of using AR requires that the conformal subset of virtual content is perceived in the correct physical location. Conformal virtual content must be correctly associated with the physical location, object, or person intended to be augmented. In this report, we provide emerging recommendations aimed at improving spatial perception of virtual content.

15. SUBJECT TERMS
augmented reality, AR, tailored information representation, depth perception, Integrated Visual Augmentation System, visual cues to distance

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Michael Geuss
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code)
Unclassified	Unclassified	Unclassified	UU	22	(410) 278-5892

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

1. Introduction

Augmented-reality (AR) displays render virtual content overlaid on the real world. AR offers great potential for Soldiers to immediately perceive relevant tactical information without the need to consult a physical map and other reference material, or for Soldiers to divert their eyes away from the immediate environment. In AR, virtual content may be rendered so that it appears to be co-located with the physical environment (conformal presentation), or as an overlay so that it appears to be on a 2-D surface that is not necessarily aligned with the physical environment (e.g., floating information in heads-up displays). Realizing the potential benefits of using AR to display virtual content in a conformal manner requires that virtual content is perceived in the correct physical location; it must be correctly associated with the location, object, or person intended to be augmented. In this report we provide emerging recommendations aimed at improving spatial perception of virtual content rendered in a conformal manner.

2. Bottom Line Up Front

Through programs like the Integrated Visual Augmentation System, the US Army is seeking to improve Soldier situational awareness (SA) using AR displays. AR displays *supplement* the physical environment by adding spatial virtual content that can draw attention to or describe a physical location, object, or person. To improve tactical performance, virtual content must be implemented correctly for improved understanding of the location, distance, and heading of red and blue forces as well as the location, distance, and heading to key landmarks and other places of interest. That is, realizing the potential benefits of AR requires that Soldiers can appropriately associate virtual content with the physical spatial environment (location, object, or person) intended to be augmented.

Unfortunately, a large body of research in AR and virtual reality (VR) has demonstrated that users typically misperceive the location of virtual content, either greatly underestimating or overestimating how far virtual content is from the observer (Loomis and Knapp 2003; Swan and Gabbard 2005; Geuss et al. 2010, 2012; Livingston et al. 2013 for review; Diaz et al. 2017; Pointon et al. 2018). Rendering virtual content based purely on physical geometry without careful consideration of perceptual cues to distance is likely to result in ambiguity about the true location of virtual content.

Furthermore, misperceptions of distance are even greater for non-line-of-sight virtual objects (e.g., X-ray vision) because there are conflicting cues to distance when placing virtual content behind physical barriers (Kirkley 2003; Swan et al. 2007; Livingston and Moser 2013).

Clearly there are significant challenges involved in representing virtual content in augmented or fully immersive VR technologies in ways that facilitate accurate spatial perception for users. However, there is evidence that human errors for space perception in AR—distance compression and overestimation—can be minimized by rendering virtual content in ways that leverage natural distance cues (Diaz et al. 2017). Based on current research, we make the following emerging recommendations to improve the accuracy of human spatial perception using AR:

1) Virtual content should be clearly referenced to the ground plane, through rendering the content on the ground plane, as attached to the ground plane through shadows, or on real-world objects attached to the ground plane. In general, virtual content should *not* appear to be floating in the air untethered (Fig. 1).

Fig. 1 (top) Example of an object whose position is perceptually ambiguous. The box could be interpreted to be either floating above the ground and on the deck or on the ground-plane and "inside" the wall. (bottom) The addition of a shadow, which grounds the object to the floor, reduces ambiguity about the object's location.

2) The visual angle of virtual content should mimic real-world content based on distance as appropriate to the task and decision context (e.g., determining depth or distance). In the real world, the visual angle subtended by an object on the retina is a function of the size of the object and distance to that object. This distance/size relationship should be replicated in virtual environments when targets are close enough to be visible. That is, the angle subtended on the eye by an object of a given size will increase as the distance to the object decreases and vice versa. In general, virtual content should *not* subtend a fixed angle that does not change with distance. In Fig. 2 the angular size of the horizontal bars reflects distance.

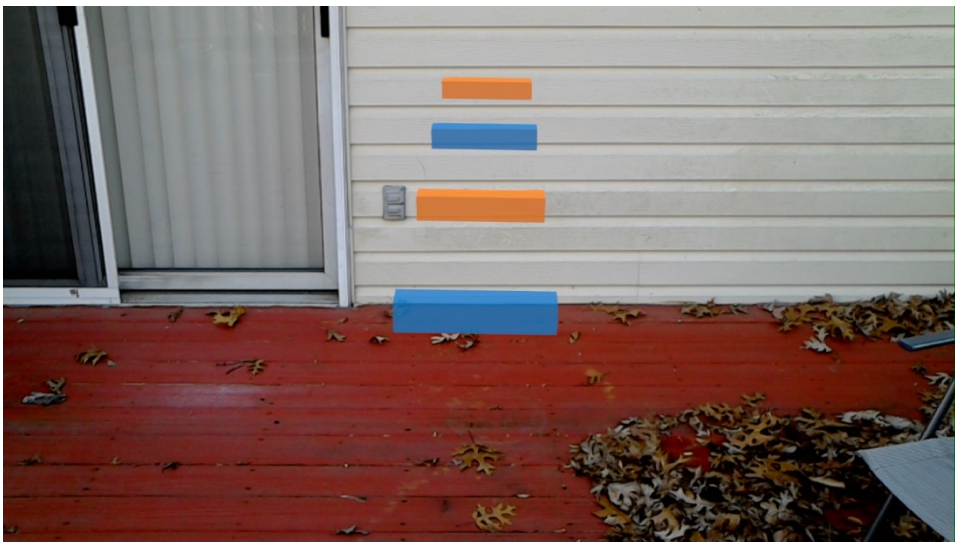

Fig. 2 Virtually rendered rectangles of the same "physical" size following the relationship between size–distance (constant visual angle). This relationship between size and distance can be used by the perceptual system to indicate the distance to objects.

3) Transparency of virtual objects can be increased to indicate farther distances (Fig. 3). Figure 3 demonstrates use of transparency that results from aerial perspective (or atmospheric perspective) or the reduction in contrast, detail, and color at distance to convey a greater distance for the cube on the right than the cube on the left despite being rendered at the same physical distance from the observer. When manipulating transparency of objects, this effect on distance perception should be considered.

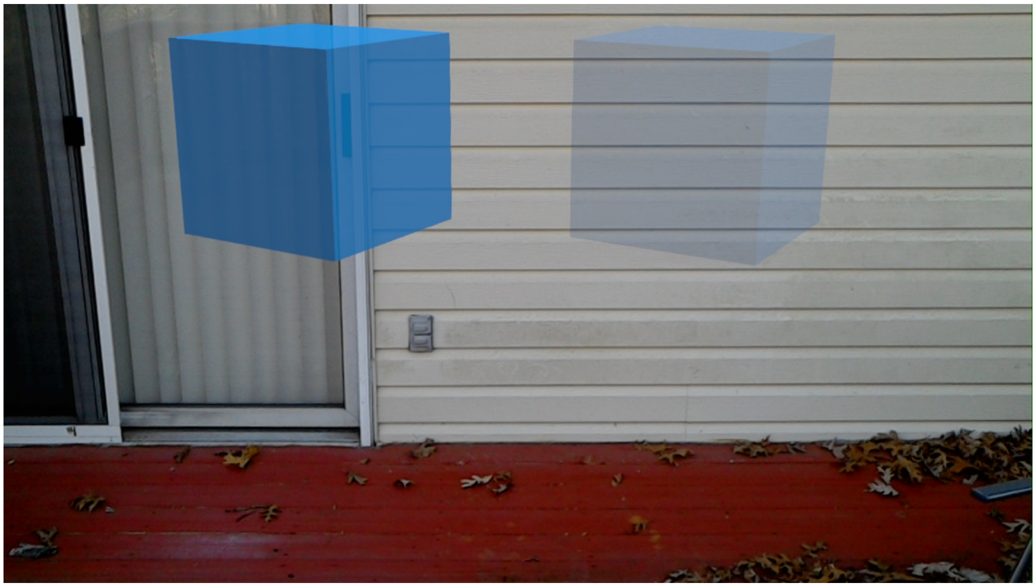

Fig. 3 Aerial perspective is defined as the reduction in contrast for objects that are farther away. This relationship can be used in AR applications (where all virtual content has some transparency) to manipulate perceived distance to targets.

4) Reducing the saliency of the physical surfaces or rendering images that imply a gap or window in the physical surfaces that occlude virtual content may aid in more-accurate perception of non-line-of-sight virtual content (Fig. 4).

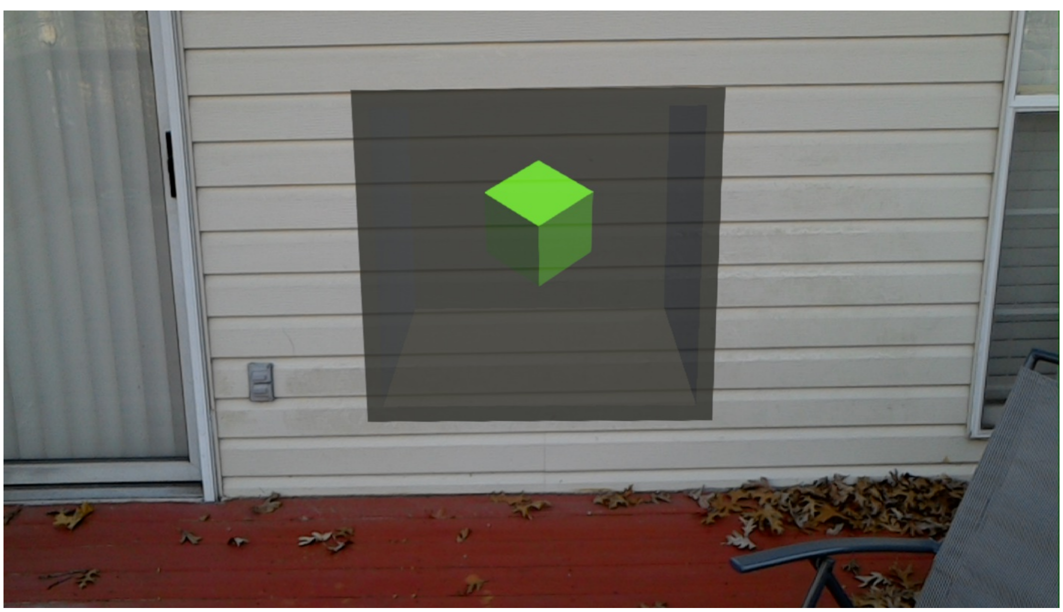

Fig. 4 Rendering techniques, like creating a virtual "cut-out", may reduce the perceptual conflict when viewing virtual content beyond one's line of sight. The cut-out makes it more plausible that the virtual object is located beyond the physical wall.

5) Objective measures of user’s spatial perception are generally preferable to user evaluation or subjective reports.

3. Research Gaps

The previously discussed recommendations are described as emerging. Multiple empirical papers have reported errors in distance estimation and how these errors relate to the presence of various cues. Yet the majority of these prior studies have used a limited subset of possible experimental conditions. Specifically, previous results are limited to relatively short distances, mostly indoor environments, and environments with a relatively flat ground plane. The recommendations would be strengthened by empirical research that investigates the following:

- The influence of additional perceptual cues and combinations of perceptual cues. The majority of studies have only investigated the influence of a single cue—ground plane, aerial perspective, and the like—on distance perception (Tsuda et al. 2005; Livingston et al. 2009; Diaz et al. 2017).

- Perceived distance to targets located farther from the observer. Current AR distance-perception results are limited to distances less than 45 m for non-line-of-sight-targets and 115 m for direct-view targets. (Livingston et al. 2003).

- Explicit testing of the effects of environmental conditions (e.g., fog and other weather conditions, uneven ground plane, and time of day) on space perception. Current results are largely limited to *indoor spaces viewed from a standing position*. It is critical for future work to also assess distance perception with AR in outdoor environments.

- Multiple measures of space perception (e.g., verbal estimation, perceptual matching, making judgments of possible actions, and reaching/walking to target) because it is a multidimensional construct (e.g., can be used to guide action or describe absolute dimensions). Multiple measures should be employed and evaluated together within studies to provide a better understanding of the magnitude of and potential causes for errors in distance perception.

4. Enhancing Space Perception in Augmented-Reality Displays: Initial Considerations

In this section we provide more detail regarding the recommendations discussed previously with citations and greater explanation of phenomena for those who wish to gain a more detailed understanding of the recommendations.

When using AR displays, it is important to remember that the positioning of all virtual content in physical space is simulated (it is being viewed on a flat screen). Virtual content is rendered on a screen close to one's eyes to appear as if it located in the real world. Whereas hardware capabilities like latency or field of view (FOV) have been shown to influence perceived location, these hardware limitations are often restricted by current technology and out of the designer's control. However, software choices regarding how to render a virtual object can alter the apparent location of that object in real space and thus influence SA.

Errors in perceived location of virtual content are well documented in AR and VR displays (Loomis and Knapp 2003; Swan and Gabbard 2005; Geuss et al. 2010, 2012; Livingston et al. 2013 for review; Diaz et al. 2017; Pointon et al. 2018). Research in this area has typically focused on egocentric distance perception, or the distance between the observer and the object. Users often estimate egocentric distances as shorter than they actually are by as much as 50% in VR (Geuss et al. 2012 for review) and by 15%–30% in AR depending on, respectively, whether the object is within direct view (Diaz et al. 2017) or occluded by real-world surfaces (Sandor et al. 2010; Livingston et al. 2013 for review). The degree to which perceived distances are compressed varies by the absolute distance to targets, the sophistication of technology employed in the experiment, and the methods used to assess distance perception. Importantly, design choices for how to render the virtual content can allow users to naturally perceive distances to objects by rendering images in ways that align with natural cues to distance, or design choices can interfere with these cues and create difficulty in determining distance to objects. The informed designer needs to be aware of these cues, their effects, and potential for alignment and mismatches.

To inform the development of tailored interactions between Soldier and intelligent but uncertain artificial-intelligence/machine-learning-generated information, researchers at the US Army Combat Capabilities Development Command Army Research Laboratory's Human Research and Engineering Directorate are conducting fundamental research to identify generalizable principles for how and when uncertain information should be represented to improve decision-making performance. As part of this effort and drawing from our expertise in visual perception and spatial cognition, we have outlined several emerging recommendations aimed at improving perceived location of virtual content through careful consideration of the effects of missing or conflicting perceptual cues to distances that are typical in AR/VR applications. Improving the accuracy of the perceived location of virtual content should lead to a corresponding improvement in users' ability to associate virtually rendered target-related information with the physical target itself. This ability is a critical function of AR displays, and it must be supported for targets varying in proximity and visibility, from those nearby and within direct view to those farther from the observer or occluded by physical barriers, specifically:

1) Virtual content should be clearly referenced to the ground plane, through rendering the content on the ground plane, as attached to the ground plane through shadows, or on real-world objects attached to the ground plane. In general, virtual content should not appear to be floating in the air untethered (Fig. 1).

Virtual content can be placed anywhere in the visual field, and designers often take advantage of this freedom by placing virtual content that appears to be floating above the ground, where there may be less visual clutter. However, without properly "grounding" a virtual object, research shows that participants report the object as closer than its true location (Diaz et al. 2017). Floating objects are perceptually ambiguous because they fail to use a strong cue to distance; for example, the regularity of a ground surface. When objects are in contact with the ground plane, people can use several cues to determine how far away the target is, including texture gradient, horizon-distance relation, and horizon ratio (Thompson et al. 2011 for overview). Texture gradient describes the phenomena where the scale of pattern decreases as distance increases, and is most informative when objects are located on or connected to the ground plane. Assuming Euclidean perception of space holds, the horizon–distance relationship can be described by

$$D = h * \cot \theta, \tag{1}$$

where the distance to an object on the ground plane (D) is determined by the angle of declination (θ) from the horizon to the object and observer's eye height (h). If an object is not located on the ground plane, observers are unable to use these distance cues.

Placing objects on the ground plane or using rendering techniques to ground the object can reduce error in perceived location (Kirkley 2003; Livingston and Moser 2013; Diaz et al. 2017). Diaz demonstrated that applying shadows to virtual targets in AR reduced error in distance estimation by 80%. Accurately modelling lighting to render accurate shadows can, however, be computationally expensive, and uneven ground surfaces reduce the utility of shadows that may be hidden behind hills, for example. Another option to realize the benefits of the ground plane is to display virtual content simply as being supported by objects that are connected to the ground (Meng and Sedgwick 2002). Smallman et al. (2001) recommended "grounding" virtual content by rendering a pole that attaches the virtual object to the ground plane.

Overall, the literature suggests that "grounding" virtual content is beneficial for reducing errors in distance perception, whether it is achieved by placing the virtual object on the ground, using cast shadows to project the object's location to the ground plane, or attaching the virtual content directly to objects located on the ground plane.

2) The visual angle of virtual content should mimic real-world content based on distance as appropriate to the task and decision context (e.g., determining depth or distance). In the real world, the visual angle subtended by an object on the retina is a function of the size of the object and distance to that object. This distance–size relationship should be replicated in virtual environments when supporting natural depth or navigational judgements. That is, the angle subtended on the eye by an object of a given size will increase as the distance to the object decreases and vice versa. In general, virtual content should *not* subtend a fixed angle that does not change with distance. In Fig. 2 the angular size of the horizontal bars reflects distance.

When using stereographic displays and binocular viewing conditions, the size of virtual objects should not break the size–distance invariance relationship. Size and distance are related such that the size of an object can be used to determine the distance to that object and thus its location. This relationship takes the form

$$s \approx 2d * \tan\frac{\theta}{2} \quad (2)$$

or

$$d \approx \frac{1}{2s} * \cot\frac{\theta}{2}, \quad (3)$$

where *s* is the size of the object along the vertical axis, *d* is equal to the distance to the target, and *theta* describes the visual/optical/retinal angle subtended by the object (Boring 1940; Thompson et al. 2011; Erkelens 2017). Size–distance invariance posits that people can determine the distance to an object primarily on its retinal size, even when other distance cues are lacking, suggesting it is a strong cue to distance. Further, the relative size differences among objects of known familiar size can help users to determine the distance to virtual targets. Under monocular viewing, the size of the object should change in line with Eqs. 2 and 3.

The size of targets should *not* be manipulated in ways that break the described relationships; for example, by keeping a virtual object's apparent size constant as distance to the object varies. Such artificial altering of size can result in users being unable to use size–distance invariance, relative size, or familiar size as effective distance cues.

3) Transparency of virtual objects can be increased to indicate farther distances (Fig. 3). Figure 3 demonstrates use of transparency that results from aerial perspective (or atmospheric perspective) or the reduction in contrast, detail, and color at distance to convey a greater distance for the cube on the right than the cube on the left despite being rendered at the same physical distance from the observer. When manipulating transparency of objects, this effect on distance perception should be considered.

Most virtual content in AR is presented as transparent or semi-transparent, and the transparency of objects can be used as a method to manipulate perceived distance to near and far objects (Cipiloglu et al. 2010). This method works to alter distance perception because the visual system uses aerial perspective, or the haziness of colors and textures at far distances, as a cue to distance (Cutting and Vishton 1995). In natural viewing conditions, aerial perspective is only useful for far distances that are about 100 m or more from the observer where fog and atmospheric interference builds up enough to reduce contrast of the rendered object. It has been suggested that simulating fog or altering transparency of virtual objects could alter distance perception for near distances, but more work is needed to confirm its relative influence (Diaz et al. 2017). The effect of transparency on distance perception should be considered when manipulating transparency to represent other information (e.g., uncertainty of target location).

4) Reducing the saliency of the physical surfaces or rendering images that imply a gap or window in the physical surfaces that occlude virtual content may aid in more accurate perception of non-line-of-sight virtual content (Fig. 4).

When virtual content is rendered to appear beyond a physical surface, the user experiences conflicting perceptual cues to the object's true location. Perspective, ground-plane interactions, size of targets, and stereopsis might all cue the user that the object is located farther than the physical barrier. However, the physical barrier is still visible, which creates a conflict that makes the virtual content appear as if it is closer than the barrier. That is, the virtual content will appear to occlude part of the physical object, implying that the virtual content is located in front of that physical object. Much work on "X-ray vision" during the early 2010s attempted to create rendering solutions that would deconflict occlusion of virtual objects by physical barriers, implementing solutions that would reduce the appearance of the physical barrier or add additional indicators of distance (Livingston et al. 2013 for review).

Attempts to reduce saliency of physical barriers to occlude virtual targets involve "cutaway" techniques, which render virtual images on the surface of the physical barrier to make it appear as if there is a hole in that barrier (Fig. 4). These techniques have also been demonstrated to improve perceived spatial dimensions of occluded virtual content (Schall et al. 2009). However, these techniques can be computationally expensive. Alternatively, one could enhance other cues to distance by rendering shadows for reasons discussed previously, rendering a virtual grid on the ground plane, or through rendering tram lines. Representing a virtual grid on the ground plane has the benefit of allowing the ground plane to be used as a cue to distance, as discussed previously, but it also increases visual clutter. Tram lines, which are two parallel virtual lines that extend from the user, act much like ground grids but take advantage of linear perspective and relative size (between object and lines) to determine distance. It is unclear, however, whether perception of tram lines or a virtual grid are not themselves impacted by a conflict of perceptual cues and create a sense of a truncated ground plane. Unfortunately, there has also been little investigation of the effectiveness of these techniques in current commercial off-the-shelf AR displays that have larger FOVs, making it unclear whether the benefit of these techniques is preserved or whether other implementation methods, like extending virtual markers above physical barriers when possible, are viable.

5) Objective measures of perceived location are preferable to user evaluation or subjective reports.

How do we evaluate whether a system is portraying virtual content in a manner that allows users to correctly associate virtual content with the physical object being described? Distance perception in AR and VR has been assessed using both measures of absolute and relative distance perception. Measures of absolute distance require participants to quantify an interval using an external scale (e.g., some metric unit), whereas measures of relative distance require participants to compare two visible intervals (Is one object closer than another?). For the purposes of AR applications that require associating virtual content with a specific physical object, it is arguably more important that observers correctly perceive relative distances. Visual matching tasks are often used to assess perception of relative distance. Participants may be asked to physically move real objects to be an equal distance from them as the virtual content (but in a different dimension), or they may adjust the distance to virtual content to align the virtual object with a physical marker. Errors in distance estimation are computed by calculating the difference between the recorded distance to the virtual object and the true distance to the real-world reference (Jones et al. 2008; Geuss et al. 2012; Diaz et al. 2017). These types of distance-matching procedures provide objective and reliable metrics of users' perceived relative distances without requiring participants to describe their own perceptions.

Verbal reports are another method for assessing distance perception, which require users to translate visible dimensions into numeric representation and are incredibly variable (Kunz et al. 2009). Another method requires participants to walk without sight to the location of the virtual object. Such "blind walking" is difficult to use for far distances (greater than ~12 m) or for targets beyond physical barriers. Very little work has evaluated distance perception for targets beyond 100 m, and more research is needed to determine appropriate measures for evaluating perception of such large distances.

The research fields of VR and especially AR are still maturing; as a result, there are still gaps in the literature and many opportunities for improved recommendations as technology advances. However, there is clear evidence in the existing literature that displaying virtual content in a way that allows for clear and accurate distance perception is a major challenge. We have provided several recommendations for display design that emerge from existing research, as well as potential avenues for further empirical investigation.

5. Conclusion

Augmented reality has great potential for Soldiers to immediately perceive tactical information in space without diverting attention away from the physical environment. To realize this benefit, however, conformal virtual content needs to be correctly associated with the physical environment intended to be described by that virtual content. In this report we have discussed relevant literature for emerging recommendations. This prior work 1) demonstrated that perceived location of virtual content is not always veridical and 2) implementation methods that capitalize on our understanding of visual perception to reduce this error. In addition, we identified multiple research gaps for space perception in AR. This includes the effectiveness for combining distance cues, targets that are far away and out of sight, and the impact of the environment (e.g., terrain, urban, or rural) and environmental conditions (e.g., time of day or weather).

Based on the limited relevant research in AR, we have provided initial recommendations for simple rendering techniques that can improve Soldiers' perception of virtual objects' locations. Reducing errors in the perceived location of virtual content will lead to improved association between virtually represented information and the physical environment being described.

6. References

Boring EG. Size constancy and Emmert's law. Am J Psychol. 1940;53(2):293–295.

Cipiloglu Z, Bulbul A, Capin T. A framework for enhancing depth perception in computer graphics. Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization; 2010 July; Los Angeles, CA. p. 141–148.

Cutting JE, Vishton PM. Perceiving layout and knowing distances: the integration, relative potency, and contextual use of different information about depth. In: Perception of space and motion. Cambridge (MA): Academic Press; 1995. p. 69–117

Diaz C, Walker M, Szafir DA, Szafir D. Designing for depth perceptions in augmented reality. Proceedings of the IEEE International Symposium on Mixed and Augmented Reality (ISMAR); 2017 Oct; Nantes, France. p. 111–122.

Erkelens CJ. Perspective space as a model for distance and size perception. i-Perception. 2017;8(6):2041669517735541.

Furmanski C, Azuma R, Daily M. Augmented-reality visualizations guided by cognition: perceptual heuristics for combining visible and obscured information. Proceedings of the International Symposium on Mixed and Augmented Reality; 2002 Oct; Darmstadt, Germany. p. 215–320.

Geuss M, Stefanucci J, Creem-Regehr S, Thompson WB. Can I pass? Using affordances to measure perceived size in virtual environments. Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization; 2010 July; Los Angeles, CA. p. 61–64.

Geuss MN, Stefanucci JK, Creem-Regehr SH, Thompson,WB. Effect of viewing plane on perceived distances in real and virtual environments. J Exp Psychol Hum Percept Perform. 2012;38:1242.

Jones JA, Swan JE, Singh G, Kolstad E, Ellis SR. The effects of virtual reality, augmented reality, and motion parallax on egocentric depth perception. Proceedings of the 5th Symposium on Applied Perception in Graphics and Visualization; 2008 Aug; Los Angeles, CA. p. 9–14.

Kirkley S. Augmented Reality Performance Assessment Battery (ARPAB) [doctoral dissertation]. [Bloomington (IN)]: Indiana University; 2003.

Kunz BR, Wouters L, Smith D, Thompson WB, Creem-Regehr SH. Revisiting the effect of quality of graphics on distance judgments in virtual environments: a comparison of verbal reports and blind walking. Atten Percep Psychol. 2009;71(6):1284–1293.

Livingston MA, Ai Z, Swan JE, Smallman HS. Indoor vs. outdoor depth perception for mobile augmented reality. Proceedings of the 2009 IEEE Virtual Reality Conference; 2009 Mar. Lafayette, LA. p. 55–62.

Livingston MA, Moser KR. Effectiveness of occluded object representations at displaying ordinal depth information in augmented reality. Proceedings of the IEEE Virtual Reality Conference; 2013 Mar; Orlando, FL. p. 107–108.

Livingston MA, Dey A, Sandor C, Thomas BH. Pursuit of "X-ray vision" for augmented reality. In: Human factors in augmented reality environments. New York (NY): Springer; 2013; p. 67–107.

Livingston MA, Swan JE, Gabbard JL, Hollerer TH, Hix D, Julier SJ, Baillot Y, Brown D. Resolving multiple occluded layers in augmented reality. Proceedings of the Second IEEE and ACM International Symposium on Mixed and Augmented Reality; 2003 Oct. p. 56–65.

Loomis JM, Knapp JM. Visual perception of egocentric distance in real and virtual environments. Virtual Adapt Environ. 2003;11:21–46.

Meng JC, Sedgwick HA. Distance perception across spatial discontinuities. Percep Psychophys. 2002;64(1):1–14.

Pointon G, Thompson C, Creem-Regehr S, Stefanucci J, Bodenheimer B. Affordances as a measure of perceptual fidelity in augmented reality. Proceedings of the IEEE VR 2018 Workshop on Perceptual and Cognitive Issues in AR (PERCAR); 2018 Mar; Reutlingen, Germany. p. 1–6.

Sandor C, Cunningham A, Dey A, Mattila VV. An augmented reality X-ray system based on visual saliency. Proceedings of the 2010 IEEE International Symposium on Mixed and Augmented Reality; 2010 Oct. p. 27–36.

Schall G, Mendez E, Kruijff E, Veas E, Junghanns S, Reitinger B, Schmalstieg D. Handheld augmented reality for underground infrastructure visualization. Pers Ubiquitous Comput. 2009;13(4):281–291.

Smallman HS, St John M, Oonk HM, Cowen MB. Information availability in 2D and 3D displays, IEEE Computer Graphics and Application. 2001;21:51–57.

Swan JE, Gabbard JL. Survey of user-based experimentation in augmented reality. Proceedings of 1st International Conference on Virtual Reality; 2005 July. Vol. 22. p. 1–9.

Swan JE, Jones A, Kolstad E, Livingston MA, Smallman HS. Egocentric depth judgments in optical, see-through augmented reality. IEEE Transactions on Visualization and Computer Graphics. 2007;13(3):429–442.

Thompson W, Fleming R, Creem-Regehr S, Stefanucci JK. Visual perception from a computer graphics perspective. Boca Raton (FL): AK Peters/CRC Press; 2011.

Tsuda T, Yamamoto H, Kameda Y, Ohta Y. Visualization methods for outdoor see-through vision. Proceedings of the 2005 International Conference on Augmented Tele-existence; 2005 Dec. p. 62–69.

List of Symbols, Abbreviations, and Acronyms

2-D	2-dimensional
3-D	3-dimensional
AR	augmented reality
FOV	field of view
SA	situational awareness
VR	virtual reality

1 (PDF) DEFENSE TECHNICAL
INFORMATION CTR
DTIC OCA

1 (PDF) CCDC ARL
FCDD RLD CL
TECH LIB

1 (PDF) CCDC DAC
FCDD DAS LH
T DAVIS
BLDG 5400 RM C242
REDSTONE ARSENAL AL
35898-7290

1 (PDF) CCDC
FCDD PPH
J THOMAS
6662 GUNNER CIRCLE
ABERDEEN PROVING
GROUND MD
21005-5201

1 (PDF) USAF 711 HPW
711 HPW/RH K GEISS
2698 G ST BLDG 190
WRIGHT PATTERSON AFB OH
45433-7604

1 (PDF) USN ONR
ONR CODE 341 J TANGNEY
875 N RANDOLPH STREET
BLDG 87
ARLINGTON VA 22203-1986

1 (PDF) USA NSRDEC
RDNS D D TAMILIO
10 GENERAL GREENE AVE
NATICK MA 01760-2642

1 (PDF) OSD OUSD ATL
HPT&B B PETRO
4800 MARK CENTER DRIVE
SUITE 17E08
ALEXANDRIA VA 22350

15 (PDF) CCDC ARL
FCDD RLH
J LANE
Y CHEN
P FRANASZCZUK
K MCDOWELL
A MARATHE
FCDD RLH F
J GASTON
FCDD RLH FA
A DECOSTANZA
FCDD RLH FC
M GEUSS
S MOORE
FCDD RLH FE
E HOLDER
D HEADLEY
J BAKDASH
L COOPER
FCDD RLH P
K OIE
A EVANS