Visualization Using Field of Light Displays: Opportunities and New Questions

Matthew Hamilton

Abstract

Visualization techniques are typically evaluated on conventional 2D displays. Current immersive display technology such as head-mounted displays (HMDs) and existing (and future) 3D field of light displays (FoLDs) can present visual information with additional perceptual cues not found in 2D displays. We review immersive technology and existing studies which suggest that additional perceptual cues (*e.g.* stereoscopy and focal cues) from 3D displays can enhance some visualization tasks' performance. This suggests potential new studies which measure the effect of additional perceptual cues and their influence on effectiveness of visualization methods. We consider the problem of visualizing data which contains interesting structures across multiple scales. We show how immersive and FoLDs provide an opportunity to answer some new questions related to this problem. We hypothesize that the additional perceptual cues of FoLDs can enhance perception of shape structures across multiple scales and we suggest several possible approaches for studying this.

Keywords: 3D Display, light field display, perception

Index Terms: K.6.1 [Management of Computing and Information Systems]: Project and People Management—Life Cycle; K.7.m [The Computing Profession]: Miscellaneous—Ethics

1 Introduction

Visualization is often used to help human users recognize patterns in complex datasets. Patterns that must be recognized often cannot be narrowly defined *a priori*, thus their recognition cannot be simply computed. Given an effective visual mapping, an informed human can detect relevant patterns both quickly and accurately, typically suggesting that the mapping supports efficient dynamic cognitive processes. This is especially important in scenarios such as battlespace awareness where rapid and effective decision making is critical [21].

Historically, effective visual mappings have been largely studied in the context of visualization using conventional displays. More recently, studies have shown that advanced displays can provide some advantages in terms of task performance for some visual mappings [23]. In this case, advanced display technology includes glasses-worn stereo displays and virtual/augmented reality head-mounted devices (HMD). These displays provide a greater subset of the visual cues experienced by a human observer when viewing real-world scenes. These displays have been criticized, however, for having issues in terms of causing visual fatigue and additional discomfort and muscular fatigue in the case of the HMDs.

Recently, displays which address these issues have been targeted by several development efforts. Field of Light Displays (FoLDs) strive to provide a visual experience which resembles that of looking at a window into a virtual world. These displays purport to provide the same perceptual cues as experienced when viewing a real-world scene.

Given their apparent advantages, as these displays become more pervasive, it is likely that they will serve to enhance the visualization of complex datasets in terms of task performance. This generates new questions and new possibilities. Studies to further confirm the suspicion of improved task performance must be performed as these displays become usable and available. To this end, we consider the problem of visualizing large datasets which contain features at multiple scales and consider what mappings might allow for the most effective visualizations on these displays.

In this paper, we review 3D display technology in terms of the perceptual capabilities of various device types. We next review studies of the effectiveness of 3D displays for visualization. We next discuss our prediction that high quality FoLD displays will enable enhanced visualization capabilities. We give an overview of how these new displays will need to be studied in order to develop the next generation of effective visualization techniques. Finally, we specifically consider the problem of visualizing complex multi-scale data. We hypothesize that FoLD displays will enable an improved ability to attend to the full range of scales within an image and may inspire new strategies for developing visual mappings to support exploration of features at varying scales.

2 Related Work

2.1 3D Display Preliminaries

The ideal computer display would be capable of producing patterns of light exactly as it is encountered in viewing natural imagery [4,19]. This premise has led to the concept of a 3D Display Turing Test [35]: "Can you distinguish the 3D scene geometry you perceive from an advanced display from the geometry you perceive when viewing the real world?" [4]. In context of such an ideal display, we consider the concept of a *light field* or *field of light*, a function which describes the amount of light flowing in every direction and every point in space within the domain of the function.

In practice, various display technologies, including conventional 2D displays, produce a field of light in only an approximate fashion. A conventional 2D display is only able to control light intensity and color in terms of space (per pixel). In contrast, field of light displays (FoLDs) provide this control in both space and direction. In Fig. 1, we see a depiction of a conventional 2D display pixel which can only represent a single color and intensity (red in this case), while the FoLD pixel can represent multiple colors and intensities in different directions. A conventional display's resolution measures its ability to represent light variation in space, which we refer to as *spatial resolution*. A FoLD has a *directional resolution*, defined in terms of the number of individual directions in which it can control intensity and color of light.

One class of FoLDs represents direction of light in only the horizontal direction. These are referred to as horizontal-only parallax displays, while displays which can direct light in both a horizontal and vertical direction are referred to as full parallax displays.

2.2 Perceptual Aspects of Displays

The human visual system uses a number of cues to extract information about a visual environment from the patterns of light stimulation imaged at the eyes. Conventional 2D displays provide a sense of 3D through simple monocular depth cues. Some examples of these are perspective (cue based on converging of parallel lines at distance), occlusion (cue based on object overlap order), texture, shading and motion [40]. A single fixed image on a conventional 2D display does not support focus cues nor motion cues. In real-world viewing, binocular cues such as disparity and vergence in additional to monocular cues like focus and motion are used to determine depth structure in visual scenes [34].

The more closely a built display approximates the field of light (FoL), the more of the cues associated with realistic 3D perception can be provided. Several works provide comprehensive overviews of 3D display technologies and the various cues they provide [12, 16]. The simplest 3D displays provide additional stereoscopic cues via a single conventional 2D view to each eye. This is provided through viewing conventional displays with glasses and using various techniques to multiplex the left and right eye [12]. Autostereoscopic approaches provide a unique view per eye without glasses. Conventional consumer virtual (VR), mixed and augmented (AR) reality head mount displays (HMDs) provide a single view per eye.

It is known that these stereoscopic displays cause fatigue and strain, attributable to the accommodation-convergence (AC) conflict phenomenon [18]. Under normal viewing conditions, the eyes fixate on an object by adjusting focus (accomodation) to the depth of the object and the eyes either rotate towards each other (convergence) or away from each other in accordance with the depth of the object. AC conflict occurs in conventional stereoscopic displays because the eyes will focus at the display plane to create the sharpest image, while the eyes will still rotate towards or away from each other as normal, driven by disparity between the left and right eye image. FoLDs which provide focal cues have been shown to prevent AC conflict [31].

Using head-tracking, via HMD sensors or external means, these stereo displays can be expanded to also display 3D structure from motion cues. This does not prevent AC conflict, but provides additional depth information and can provide a compelling immersive visual experience. With HMDs, the weight of the worn device can lead to further discomfort depending on its weight and time worn. Without HMDs, using head-tracking provides greater comfort, but is limited to a single viewer in terms of providing structure from motion cues.

FoLD displays have the added advantage of providing focal cues. On the surface, this may appear to be a trivial advantage, beyond it reducing AC-based eyestrain in younger viewers [30]. However, several studies have shown that focal cues work with stereoscopy to provide an overall improved shape perception capability [4, 27]. Studies that have shown focal cues contribute significantly to perception of scale in a scene [17, 42]. It has also been shown that AC conflict can actually reduce performance in some visual tasks, highlighting an additional disadvantage to the associated eyestrain and further underscoring the importance of focal cues [4].

In summary, 3D and immersive displays provide more perceptual cues than conventional 2D displays. FoLDs promise to provide all these cues as well as focal cues, which are not typically found in conventional existing 3D display technology. Cues such as stereoscopic, motion and focal cues are known to individually contribute to shape perception and overall ability to understand a visual scene, providing a cumulative improvement of scene understanding when combined [34,40]. This suggests that FoLDs may have great promise in terms of enhancing the effectiveness of visualization.

2.3 Development Status of Field of Light Displays

What is desired is a 3D display which requires no glasses, but provides stereoscopic, motion and focal cues in order to eliminate the AC conflict issue. A further desire is the ability to support collaborative activities among multiple observers. This could come in the form of a tabletop configuration or even a wall-paneled design as imagined for a Holodeck [7, 19]. Field of Light Displays (FoLDs) such as lightfield and holographic displays have been proposed to meet these requirements.

In terms of development, these displays are on the cusp being usable for visualization applications. Displays with directional representation limited to the horizontal direction have been developed by a number of companies and groups such as Holografika, Looking Glass, ICT, Third Dimension Tech [3, 5, 26, 33]. These displays have compelling image quality based on current state of technology. The main detriment to these displays is the lack of vertical parallax, which is critical for tabletop or holodeck-style collaborative immersive configurations [7]. A further disadvantage is that focal cues are not fully reproduced, thus providing less natural viewing conditions as compared to full-parallax displays.

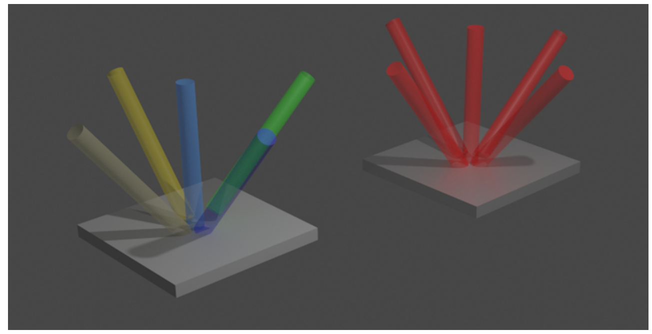


Figure 1: Pixel (right) has all rays same color and intensity, while field of light pixel (left) can control intensity and color in a directional sense.

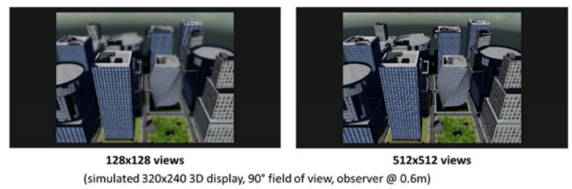


Figure 2: Illustration of how directional resolution affects the 3D Resolution [21]

Several efforts have developed full parallax light field displays, including companies such as Avalon Holographics, Ostendo, FOVI 3D (previously Zebra Imaging) and Light Field Lab [2, 22]. Significantly more pixels are required to produce quality displays in this regime, as the depth of the displays is dependent on directional resolution [43]. In order for these displays to be usable, they will require higher spatial and directional resolution to support sharp imagery with good usable depth in and out of the display (See Fig. 2). With the significant efforts being applied, these developments will soon result in usable displays.

2.4 Visualization with 3D Displays

The effectiveness of visualization methods is typically evaluated in terms of task performance [24]. It has been reported in some studies that 3D visualization on a 2D display can be ineffective [29]. In contrast, physical visualizations of real objects appears to overcome these limitation [29]. It is reasonable to assume that 3D displays would present light in a form more similar to natural imagery from physical objects than 2D displays. Given that 3D displays provide a larger range of effective perceptual cues than 2D displays, it is not unreasonable to expect that this may enable improved performance in some tasks. We review a number of studies which show improvements enabled by 3D displays.

One early study showed that the addition of stereoscopy cues improved performance in tasks related to object movement predictions in 3D [36]. Another set of studies [37, 38] showed that graph visualization tasks are improved with both motion parallax

Figure 3: Collaborative visualization [25]

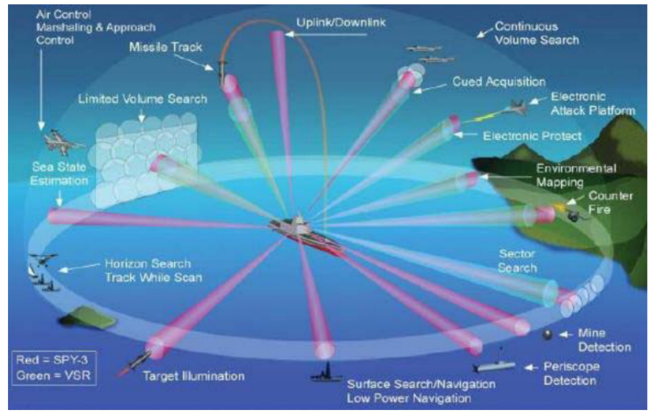


Figure 4: 3D Real Time Visual Ship and/or System Performance for Operator Full Situational Awareness [21]

(provided by head-tracking) and stereoscopic cues. With HMDs enabling these same cues, a number of studies explored their benefits for visualization. Kwon *et. al* showed improved performance of graph visualization using HMDs [23]. A recent study [41] also showed evidence that visualization in VR reduced mental workload as compared to conventional 2D mappings.

Hackett used static holograms in several studies to explore enhanced learning of 3D anatomical structure [14, 15]. The results suggest the FoL images reduce cognitive load in learning tasks. Further studies [1, 13] explored specific aspects of hologram quality in the medical simulation visualization context. Other works have considered the use of printed holograms in aiding spatial decision-making tasks [10, 11], showing distinct benefits of holographic/FoL images.

3 Investigating Visualization with 3D Displays

3.1 Complex Scene and Collaborative Visualization

Given that FoLD displays appear to support improved task performance, decreased cognitive load and greater visual comfort, it stands to reason that they will become important tools for visualization as their development continues. The defense community has long advocated for these displays for a number of challenging use cases, including complex situational awareness (*e.g.* for battle space visualization), pilot training simulation and medical applications [20, 21].

Complex situational awareness scenarios generally require the fusion of multiple data sources into a common spatio-temporal reference. In these scenarios, there is a requirement for a blended visualization of realistic models of objects with various sensor data captured, overlaying and augmenting the real-world imagery aspect. For example, in the battle space visualization use case, multiple actors such as aircraft, ships, submarines can be depicted in a complex environment potentially composed of both detailed ocean and land maps, depicted complex terrain geometry(Fig. 4). This basic scene setup is then augmented by shape volumes indicating ranges of sensor capabilities and weapon range threats, in addition to live sensor data conveying environmental parameters such as wind, sea state and visibility. Given this complexity, an effective visualization for these scenarios is required to support a range of tasks and cognitive processes which support operational decision-making.

Such decision-making is inherently collaborative, bringing together teams of experts with diverse skills and roles (Fig. 3). This requirement further broadens the range of tasks and cognitive processes that must be supported. The desire to support simultaneous effective team communication along with the extreme penalties associated with poor decisions drive a strong requirement for the visualization to reduce strain, discomfort and cognitive load in its users. This is in addition to supporting isolated task performance. A further desire is to convey real objects in the scenario with a maximal degree of photorealism, as this aids in conceptualization and team communication where technical expertise concentration fluctuates or is segmented.

3.2 Visualization of Multiscale Data

3.2.1 Problem of Visualizing Multiple Scales Simultaneously

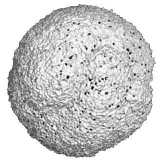
One interesting unresolved challenge in visualization revolves around multiscale data. The most challenging datasets for visualization are large, represent complex, heterogeneous phenomenon and span large ranges of spatiotemporal scales. Some examples include medical imaging data of the human body, particularly complex organs such as the brain and lungs and battlespace and other complex operations visualization. In many use cases, there is also an aesthetic requirement to maintain detail in order to preserve photorealism as much as possible in visualizations, to support communicative aspects of the visualization. It is desirable to create visual mappings which allow for users to attend to features at a range of scales within a single view of a dataset or complex scene, while preserving all the detail of the data.

The problem in these cases is that fine detail tends to obscure larger-scale features, possibly explained by perceptual masking [9]. In Fig. 5, we show three visualizations of a cellular membrane simulation data visualization [6]. These simulations are based on particle data elements.

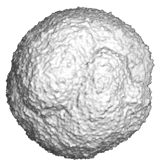
One approach to deal with the obscuring fine detail is to reconstruct a surface from discrete data elements and filter smaller scale detail. In Fig. 5 these particles are used to reconstruct a surface from the particles. The surface reconstructed without filtering preserves all the fine details of the cellular membrane formed by the particles (Fig. 5(a)). In Fig. 5 (a) and (b), we see low-pass filtered versions of the same surface. The filtering appears to clearly emphasize large scale shape structure effectively.

Simplification of fine detail in scenes may also improve visual search. Existing work suggests that lower-resolution peripheral vision plays a key role in visual search [8], suggesting that fine detail removal is already part of an existing strategy built into the visual system. In one study involving a visual searching task in VR, it was found that reducing detail improved visual search task performance; participants found it easier to pick out a target with a lower level of realism in the virtual environment [28]. These anecdotes and experimental results suggest that removing fine detail in scenes can potentially enhance perception of multiscale data for visual search and shape perception tasks.

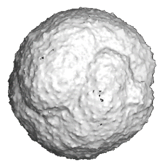
The downfall of this approach is the loss of fine detail which can still convey important information and create visual realism. This



(a) No filter



(b) Some filtering



(c) More filtering

Figure 5: Enhancement of large-scale structures by filtering small detail in cellular membrane simulation data [6]

problem of visualizing multiple scales simultaneously in complex datasets has been studied in the context of flow tube visualization [39]. In this case, a possible solution which preserves fine detail has been proposed. It was shown that global illumination can improve shape discrimination of larger features which emerge from flow tubes aggregated in space (Fig. 6). Previous work had similarly observed that ambient occlusion lighting appeared to improve visibility of larger-scale structure in molecular dynamics model visualization [32].

While global illuminations appears to improve the ability to attend to multiple scales, improves realism and can be calculated interactively, the study presented has some potential limitations. In the experiments in Weigle and Banks [39], relatively small flow tubes are aggregated to form a larger scale shape (such as a cube) (See Fig. 6). The experiments described are performed using conventional 2D displays and do not consider the effect of motion, stereoscopic or focal cues. The multiscale image stimuli used subtend a relatively small portion of the observer's visual field of view ($28^\circ x 23^\circ$). Furthermore, the relative size relationships between the small scale structure (tubes) and large scale shape explored in the experiments appear to be relatively fixed. That is, the large-scale shapes considered (cube, icosahedron and hexagonal prism) appear to have roughly the same extent. Furthermore, these shapes are rendered at a uniform distance from the virtual camera and viewed by observers at a fixed distance from the display. Thus, the large scale shape observed by the test subjects maps to roughly the same size on the retina and the smaller scale features (tubes) only span a relatively small range of sizes.

3.2.2 New Questions

One interesting question is suggested by this analysis: Is the ability to attend and perceive shape across a range of scales uniform across the entire range of perceivable scales? A more extensive study would consider perception of a larger portion of the range of scales perceivable by the human visual system. An immersive display can stimulate a much larger portion of an observer's field of view than what is typically used for on-screen studies ($30^\circ x 20^\circ$) [8]. Immersive displays and HMDs provide an opportunity to visualize across essentially the entire range of possible scales perceivable by the visual system. This provides opportunity to measure how the perceptual scale of objects in an immersive virtual world influence

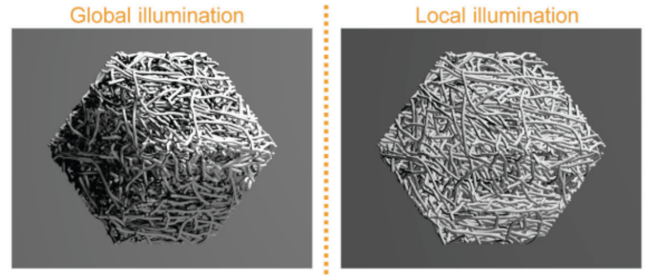


Figure 6: Large scale cube shape formed from smaller tube elements with global illumination and local illumination. The large scale cube shape appears enhanced with global illumination [39].

our ability to attend individually to different ranges of scales.

A further question involves the effect of additional perceptual cues on the ability to perceive shapes across multiple simultaneously present scales. It is known that stereoscopic, motion and focal cues contribute significantly towards shape perception. Various studies suggest that individual cues are combined neurally to give an enhanced internal 3D representation of shape [34, 40]. It seems reasonable to hypothesize that like global illumination, these cues may enable an enhanced ability to attend and perceive shape across multiple scales simultaneously. FoLDs and eventually immersive FoLD arrangements (*e.g.* HMD FoLDs and large-scale FoLD walls) will present the ability to answer these questions.

We summarize this discussion with some specific perceptual questions. Is the ability to attend and perceive shape across a range of scales uniform across the entire range of perceivable scales? If not, what does the non-uniformity look like? How can we characterize the non-uniformity (*e.g.* is it non-linear in some sense and dependent on the ranges of scales present in the image?)?. Does global illumination provide enhanced ability to perceive shape uniformly across multiple scales? Similarly, if not, how can we characterize this non-uniformity? Do additional perceptual cues such as sterescopic, motion and focal cues individually enhance/impede the ability to perceive shapes across multiple scales? Do these cues enhance multiscale perception when combined together? Does further enhancement occur when further combined with global illumination?

4 Conclusion

Visual mappings are studied largely so far in the context of conventional 2D displays. Some limited studies have considered large-scale immersive and HMD-based AR/VR display configurations which provide more of the 3D cues that are inherently present in natural imagery. These studies suggest that advanced displays show promise in terms of improving the effectiveness of visualization. The future of displays is headed towards providing imagery that more closely matches the natural world. This will be achieved by FoLDs. Preliminary studies suggest that FoLDs will allow for further improvements in visualization effectiveness.

The problem of visualizing across multiple scales presents interesting questions for immserive and FoLD-based visualization. Immersive displays allow for visual stimuli which can simultaneously activate a larger range of a viewers field of view. This allows for both peripheral and central vision to be stimulated at once. This allows for a larger range of scales to be present in a display-generated image, thus expanding the possibilities for experimental work. Furthermore, FoLD displays provide stereoscopic, motion and focals perceptual cues together at once, finally allowing us to study the combined effects of these cues on perception of shape across multiple scales. These and other interesting experiments will become possible as this new display technology becomes more widely deployed.

REFERENCES

[1] C. Allen, S. Willis, C. Hernandez, A. Wismer, B. Goldiez, G. Teo, L. Reinerman-Jones, M. Mazzeo, and M. Hackett. Holographic and Related Technologies for Medical Simulation. In D. D. Schmorrow and C. M. Fidopiastis, eds., *Augmented Cognition*, pp. 497–516. Springer International Publishing, Cham, 2019.

[2] Z. Y. Alpaslan and H. S. El-Ghoroury. Small form factor full parallax tiled light field display. 9391(July):93910E, 2015. doi: 10.1117/12.2083436

[3] T. Balogh, P. T. Kovacs, and A. Barsi. HoloVizio - True 3D display system. *Proceedings of 3DTV-CON*, pp. 3–6, 2007. doi: 10.1109/3DTV.2007.4379386

[4] M. S. Banks, D. M. Hoffman, J. Kim, and G. Wetzstein. 3D Displays. *Annual Review of Vision Science*, 2(1):397–435, 2016. doi: 10.1146/annurev-vision-082114-035800

[5] C. J. Blackwell, J. Khan, and X. Chen. 54-6: Holographic 3D Telepresence System with Light Field 3D Displays and Depth Cameras over a LAN. *SID Symposium Digest of Technical Papers*, 52(1):761–763, 2021. doi: 10.1002/sdtp.14794

[6] G. Broderick, M. Rúaini, E. Chan, and M. J. Ellison. A life-like virtual cell membrane using discrete automata. *In Silico Biology*, 5, 2004.

[7] T. Coughlin. Let's build a holodeck! *IEEE Consumer Electronics Magazine*, 9(6):90–91, 2020. doi: 10.1109/MCE.2020.3011084

[8] E. J. David, J. Beitner, and M. L. H. Võ. The importance of peripheral vision when searching 3D real-world scenes: A gaze-contingent study in virtual reality. *Journal of Vision*, 21(7):1–17, 2021. doi: 10.1167/jov.21.7.3

[9] J. A. Ferwerda, P. Shirley, S. N. Pattanaik, and D. P. Greenberg. A model of visual masking for computer graphics. In *SIGGRAPH '97: Proceedings of the 24th annual conference on Computer graphics and interactive techniques*, pp. 143–152. ACM Press/Addison-Wesley Publishing Co., New York, NY, USA, 1997. doi: 10.1145/258734.258818

[10] S. Fuhrmann, M. E. Holzbach, and R. Black. Developing interactive geospatial holograms for spatial decision-making. *Cartography and Geographic Information Science*, 42(1):S27–S33, 2015. doi: 10.1080/15230406.2015.1059174

[11] S. Fuhrmann, N. J. Smith, M. Holzbach, and T. Nichols. Investigating geospatial holograms for special weapons and tactics teams. *Cartographic Perspectives*, (63):5–19, 2009.

[12] J. Geng. Three-Dimensional display technologies. *Advances in Optics and Photonics*, 5(2):131, 2013. doi: 10.1364/AOP

[13] B. Goldiez, J. Abich, A. Carter, and M. Hackett. Perceived image quality for autostereoscopic holograms in healthcare training. In *Proc. SPIE*, pp. 10136–10136–6, 2017.

[14] M. Hackett and M. Proctor. The effect of autostereoscopic holograms on anatomical knowledge: a randomised trial. *Medical Education*, 52(11):1147–1155, 2018. doi: 10.1111/medu.13729

[15] M. Hackett and A.-h. Sttc. Medical Holography for Basic Anatomy Training. (13207):1–10, 2013.

[16] M. Hamilton, T. Butyn, and R. Baker. Holographic Displays : Emerging Technologies and Use Cases in Defence Applications. In *NATO MSG-159 2018 Annual M and S Conference*, 2018.

[17] R. T. Held, E. A. Cooper, J. F. O'Brien, and M. S. Banks. Using blur to affect perceived distance and size. *ACM Transactions on Graphics*, 29(2), 2010. doi: 10.1145/1731047.1731057

[18] D. M. Hoffman, A. R. Girshick, K. Akeley, and M. S. Banks. Vergence-accommodation conflicts hinder visual performance and cause visual fatigue. *Journal of Vision*, 8(3):1–30, 2008. doi: 10.1167/8.3.33

[19] D. Hopper. Reality and surreality of 3-D displays: holodeck and beyond. In *SID UK and Ireland Electronic Information Displays Conference*, number v, pp. 1–10, 2000.

[20] D. G. Hopper. Technology Challenges for Military and Avionics Displays. (September), 2005.

[21] C. E. T. Jr, D. R. Barstow, C. W. Honsinger, S. L. Kelley, P. G. Jones, A. G. Smith, J. R. Daniel, B. Hernandez, and C. Chinnock. AFRL-RH-WP-TR-2019-0098 Streaming Model for Field of Light Displays (SMFoLD) Phase II. 2019.

[22] M. Klug, T. Burnett, A. Fancello, A. Heath, K. Gardner, S. O'Connell, and C. Newswanger. A scalable, collaborative, interactive light-field display system. *Digest of Technical Papers - SID International Symposium*, 44(1):412–415, 2013. doi: 10.1002/j.2168-0159.2013.tb06234.x

[23] O.-H. Kwon, C. Muelder, K. Lee, and K.-L. Ma. A Study of Layout, Rendering, and Interaction Methods for Immersive Graph Visualization. 22(7):1802–1815, 2016. doi: 10.1109/TVCG.2016.2520921

[24] M. Luz, K. Lawonn, and C. Hansen. Guidelines and Recommendations for the Evaluation of New Visualization Techniques by Means of Experimental Studies. *EuroRV3: EuroVisWorkshop on Reproducibility, Verification, and Validation in Visualization*, 2017.

[25] N. Maniquis. Improving Battlespace Awareness, Reducing Warfighter Workload, and Enabling Rapid Response Through the Use of Collaborative 3D Holographic Display. In *2017 Streaming Media Field of Light Display (SMFoLD) Workshop, Sterling, VA, U.S.A.*, 2017.

[26] K. Nagano, A. Jones, J. Liu, J. Busch, X. Yu, M. Bolas, and P. Debevec. An autostereoscopic projector array optimized for 3D facial display. *ACM SIGGRAPH 2013 Emerging Technologies on - SIGGRAPH '13*, 28:1–1, 2013. doi: 10.1145/2503368.2503371

[27] A. P. Pentland. A New Sense for Depth of Field. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, PAMI-9(4):523–531, 1987. doi: 10.1109/TPAMI.1987.4767940

[28] E. D. Ragan, D. A. Bowman, R. Kopper, C. Stinson, S. Scerbo, and R. P. McMahan. Effects of field of view and visual complexity on virtual reality training effectiveness for a visual scanning task. *IEEE Transactions on Visualization and Computer Graphics*, 21(7):794–807, 2015. doi: 10.1109/TVCG.2015.2403312

[29] M. Saenz. Reexamining the cognitive utility of 3D visualizations using augmented reality holograms. 2017.

[30] T. Shibata, J. Kim, D. M. Hoffman, and M. S. Banks. The zone of comfort: Predicting visual discomfort with stereo displays. *Journal of vision*, 11(8):1–29, 2011. doi: 10.1167/11.8.11.Introduction

[31] Y. Takaki. High-density directional display for generating natural three-dimensional images. *Proceedings of the IEEE*, 94(3):654–663, 2006. doi: 10.1109/JPROC.2006.870684

[32] M. Tarini, P. Cignoni, and C. Montani. Ambient occlusion and edge cueing to enhance real time molecular visualization. *IEEE Transaction on Visualization and Computer Graphics*, 12(6), 2006.

[33] C. T. Thomas, S. Kelley, P. G. Jones, L. Sherman, L. Park, G. Sidor, D. A. Miller, and D. M. Cymstar. Full 3D Visuals for Advanced Training in Single-Seat Fighters. (17050):1–13, 2017.

[34] J. T. Todd. The visual perception of 3D shape. *Trends in Cognitive Sciences*, 8(3):115–121, 2004. doi: 10.1016/j.tics.2004.01.006

[35] A. Turing. Computing machinery and intelligence. *Mind*, 59(236):433–460, 1950. doi: 10.1007/978-1-4020-6710-5_3

[36] K. F. Van Orden and J. W. Broyles. Visuospatial task performance as a function of two- and three-dimensionaldisplay presentation techniques. *Displays*, 21(1):17–24, 2000.

[37] C. Ware and G. Franck. Evaluating Stereo and Motion Cues for Visualizing Information Nets in Three Dimensions. *ACM Transactions on Graphics*, 15(2):121–140, 1996. doi: 10.1145/234972.234975

[38] C. Ware and P. Mitchell. Visualizing graphs in three dimensions. *ACM Transactions on Applied Perception*, 5(1):1–15, 2008. doi: 10.1145/1279640.1279642

[39] C. Weigle and D. Banks. A Comparison of the Perceptual Benefits of Linear Perspective and Physically-Based Illumination for Display of Dense 3D Streamtubes. *Visualization and Computer Graphics, IEEE Transactions on*, 14(6):1723–1730, 2008. doi: 10.1109/TVCG.2008.108

[40] A. E. Welchman, A. Deubelius, V. Conrad, H. H. Bülthoff, and Z. Kourtzi. 3D shape perception from combined depth cues in human visual cortex. *Nature Neuroscience*, 8(6):820–827, 2005. doi: 10.1038/nn1461

[41] A. Wismer, L. Reinerman-Jones, G. Teo, S. Willis, K. McCracken, and M. Hackett. Workload Comparison During Anatomical Training with a Physical or Virtual Model. In *Augmented Cognition Users and Contexts*, pp. 240–252, 2018.

[42] T. Zhang, L. O'Hare, P. B. Hibbard, H. T. Nefs, and I. Heynderickx. Depth of field affects perceived depth in stereographs. *ACM Transactions on Applied Perception*, 11(4):1–18, 2014. doi: 10.1145/2667227

[43] M. Zwicker, W. Matusik, F. Durand, H. Pfister, and C. Forlines. Antialiasing for automultiscopic 3D displays. *ACM SIGGRAPH 2006: Sketches, SIGGRAPH '06*, p. 107, 2006. doi: 10.1145/1179849.1179983