Augmented Reality Knowledge Work: Towards a Research Agenda

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ABSTRACT

This paper argues that the most likely new display technology to achieve widespread adoption is augmented reality (AR) head-mounted displays (HMDs), and further argues that the way this will happen is through making them useful to knowledge workers who use them with laptops and smartphones. Research questions related to these use cases are identified.

CCS CONCEPTS

• **Human-centered computing** → **Mixed / augmented reality**; *Graphical user interfaces.*

KEYWORDS

Mixed reality, immersive.

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	Cost (US$)	**Mass** (g)	**FOV** (° horizontally)	**Angular resolution** (pixels/°)
24" HD screen at distance of 24"	$\approx$300	$\approx$3000	47	39
Microsoft HoloLens	$\approx$3000	579	$\approx$32	$\approx$44
Meta 2	$\approx$1000	420	$\approx$78	$\approx$33
Magic Leap One	$\approx$2000	345	$\approx$40	32
Leap Motion's North Star	n/a		$\approx$74	$\approx$22
eye glasses		$\approx$30		
naked eye			$\approx$160	$\approx$60

INTRODUCTION

The past $\approx$15-20 years have culminated with the widespread adoption of smartphones (Apple's iPhone, Google's Android), tablets (e.g., Apple's iPad), tablet/laptop hybrids (e.g., Microsoft Surface), as well as new software tools for cloud-based storage of documents and collaboration (e.g., Google Docs, Dropbox, Slack, Trello), and for visualizing data (e.g., Tableau), all of which have facilitated knowledge work. However, over a slightly longer timespan, researchers have proposed many other technologies that could facilitate knowledge work, including enhanced display hardware (horizontal tabletop touch-sensitive displays, wall-sized displays, rooms instrumented with multiple projectors and/or cameras and/or sensors (e.g., CAVEs), volumetric desktop displays, and head-mounted displays), as well as enhanced windowing systems and file systems, and these have so far achieved very modest adoption. This paper argues that augmented reality (AR) [26] head-mounted displays (HMDs) are the most likely new hardware platform to be widely adopted in office environments over the next 10 years, and identifies research opportunities around the use of AR HMDs by knowledge workers.

WHY AUGMENTED REALITY HMDS ?

Horizontal tabletop displays, wall-sized displays, volumetric displays, and rooms instrumented with multiple projectors and sensors all offer larger interactive display surfaces for users, but impose a significant up-front financial investment, and the inconvenience of being tied to a particular room. Tabletop displays take up significant floorspace and do not work well with physical objects or documents placed on top of them. Individuals are very unlikely to purchase such hardware for their personal use at home, further reducing the market for these technologies and impeding their adoption.

In contrast, tablets and especially smartphones were quickly and widely adopted by individuals for use in private life, because these devices are affordable, light-weight, and they make it extremely convenient to communicate with friends, find directions in a city, and consume media for entertainment. Adoption by individuals for private use accelerated the development of mobile applications for office environments, as more employees brought their personal mobile devices to work and looked for ways to use them in their work.

I speculate that AR HMDs are the next hardware platform with the greatest potential for significant adoption and impact among knowledge workers and office workers, for the following reasons: **(1)** The lower bound on their cost is determined by the mass of plastic, metal, and other materials used

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in their manufacture. Current AR HMDs such as Microsoft HoloLens (579 grams) require far less raw material than a 24 inch monitor (often over 3000 grams), and HMDs with a field-of-view (FOV) of 90 degrees or more would provide a virtual display surface far exceeding that of a monitor. The Magic Leap One headset (≈ $ 2000) is currently twice the cost of a high-end smartphone, and yet the complexity of manufacturing these devices is comparable. As more headsets are sold, their cost will approach that of a smartphone. **(2)** Governments with large military budgets will continue to invest in the development of mobile AR HMDs for use in the field, helping the technology to become more mature. **(3)** Large organizations that spend significant money for staff to travel between offices may be willing to buy AR HMDs for enhanced teleconferencing, to reduce the need for business travel. One company working on an AR teleconferencing solution is Spatial, whose promotional video [43] was viewed over 100k times in the 4 months since it was published. **(4)** Individual professionals, digital artists, or office workers who prefer to work with large physical display areas, such as two 24 inch screens, may purchase an AR HMD instead of such desktop screens, to complement and extend their laptop screen, and gain the advantage of mobile use and the ability to also extend their smartphone screen. Such individuals will then bring these headsets to their work environments, further driving adoption. **(5)** Companies creating AR HMDs are motivated by secondary markets of peripheral applications including emergency response, maintenance of machinery, monitoring of assembly lines, image-guided surgery, games[1], education, and design of 3D models for manufacturing or computer animation. End users in these markets are less likely to pay for expensive AR HMDs, however if the cost of the HMDs drops enough, these markets become available to vendors.

Items 3 and 4 are potentially the largest markets for initial adoption and therefore the strongest channels to drive AR HMDs toward maturity. Notice that these markets are made up of office workers, managers, and users who want to view content or documents on large display surfaces, i.e., *knowledge workers*.

Adoption by knowledge workers will require a few improvements to current hardware. Headsets need to be lighter [29] and more comfortable (Magic Leap One's headset has a reduced weight thanks to most of the computing power being in a pocket pack, but is still ≈ ten times heavier than a typical pair of glasses), must provide a wider FOV (Magic Leap One's FOV is ≈ 40 degrees horizontally, which is less than the 47 degree angle subtended by a 24 inch monitor at a distance of 24 inches), at a angular pixel density and crispness that is competitive with HD desktop monitors (Microsoft's HoloLens already displays at ≈44 pixels per degree, compared to a 24 inch 1920×1080 screen with 92 dpi at a distance of 24 inches yielding 39 pixels per degree). Several companies, including Microsoft and Google, are working toward solutions to these problems and have invested hundreds of millions of dollars in AR over the past ≈5 years. An additional problem with AR HMDs is their fixed focal distance, creating a vergence-accommodation conflict, making it uncomfortable to view virtual text or small details at close distance, however content at a distance of 1 meter or more suffers almost no ill

[1] One objection that could be raised is that the market for video games is quite large, however virtual reality (VR) headsets (Oculus and HTC Vive) are already more mature than AR HMDs and compatible with the gaming platform Steam. With AR HMDs lagging behind in price and performance, it's unclear how they could significantly disprupt this market over the next 10 years.

effects, and companies [3] and researchers [23, 28] are working towards a solution. Finally, Gartner's August 2018 "Hype Cycle" [17] shows "Augmented Reality" as the most mature of all the technologies surveyed.

OPPORTUNITIES FOR RESEARCHERS

The current state of AR is somewhat of a "wild west" with multiple companies (Microsoft, Google, Magic Leap, Meta, Avegant, Apple, Facebook, Intel, Amazon, Huawei) competing to develop products and establish norms. We have observed several new users of the HoloLens spontaneously reach out with their bare hands to grab or point at virtual content, and only learn with verbal explanation from a more experienced user how to instead use "gaze" (head orientation) to point and the "air tap" gesture to click, which are the interactions recommended by Microsoft[2]. Many HoloLens users are unaware that the headset can be connected via Bluetooth to a mouse and keyboard for efficient, traditional input when sitting at a desk. Meta 2's headset primarily uses bare hands for interacting with content. Leap Motion has published a series of videos[3] demonstrating experimental interaction techniques using bare hands. It is as-yet unclear which input styles will become dominant, and how AR "window managers" or immersive environments will evolve over the next 10 years. HCI researchers therefore have an opportunity to influence and catalyze the establishment of user interface norms. If knowledge work is indeed the greatest channel for wider adoption of AR HMDs, as argued in the previous section, then HCI researchers should consider focusing on knowledge work with AR HMDs as a lever to influence the course of near-term technology. The lack of norms and abundance of public interest offers a window of opportunity to plant seeds in the minds of designers, developers, and engineers with some key ideas demonstrated with research prototypes. Advanced techniques for window managers and file systems that have been previously proposed by researchers, but never gained traction commercially, could be adapted to this new hardware platform and influence the next generation of user interfaces.

[2]https://docs.microsoft.com/en-us/windows/mixed-reality/gaze

[3]https://www.youtube.com/user/leapmotion/videos , e.g., https://www.youtube.com/watch?v=LFRKEmzrzP8

A segment of the public is clearly interested in the possibilities of AR, as demonstrated by online activity: A brief 2018 video (https://twitter.com/LeapMotion/status/988749463215857664) showing a user repositioning windows in empty space [30] has been retweeted over 1000 times. A 2017 concept video [36] of a VR window management system was viewed over 100k times. A 2015 video of a 3D window management system [6] was viewed over 500k times.

We have argued that there are two main scenarios with the greatest potential for initial market penetration and wide adoption of AR HMDs: a single knowledge worker equipped with a smartphone, laptop, and AR HMD; and a group of knowledge workers conducting a teleconference meeting with AR HMDs. We now consider research questions related to the first of these two. Space limitations keep the second scenario outside the scope of this paper.

A Single User's AR HMD Extending their Physical Screens

Although it is possible to use untethered AR HMDs for mobile activities, to use bare hands for text input, and to benefit from enhanced depth cues (stereo disparity and head-coupled perspective) when viewing 3D models, most knowledge workers never work with 3D models and many of them do most of their work at a desk with a laptop, keyboard and mouse, interacting with the window management

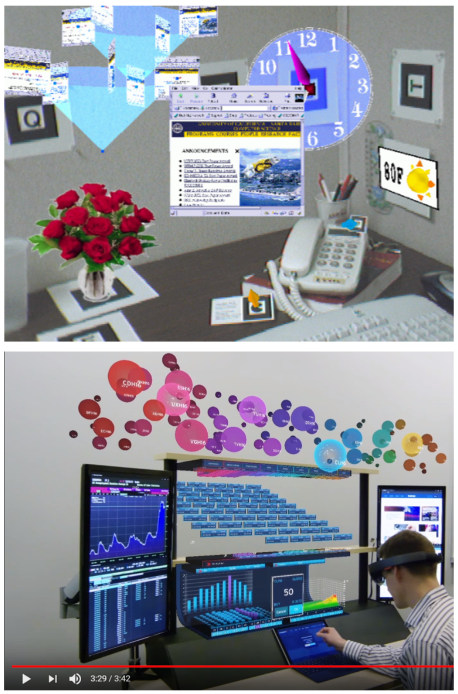

Figure 2: Combining physical desktops with AR headsets. Top: ARWin [10]. Bottom: prototype by Citi [8].

GUI of Microsoft Windows or Mac OS. The mouse is an excellent pointing device, owing to its stability, filtering out hand tremor, and having buttons that are activated in a direction perpendicular to the mouse's motion [4], while a full-size keyboard has a text input rate far higher than any mid-air typing technique. Using bare hands to point in mid-air is also tiring [22, 25]. It follows that a primary use case for an AR HMD is using it to extend the laptop's physical screen onto a larger virtual surface, possibly an infinite wall or cylinder or sphere that surrounds the user [19].

There are several examples of prototypes and concepts for surrounding a user with floating virtual windows (Figure 1) that are relevant to this scenario, however relatively little previous work has focused on virtual windows integrated with a physical desktop environment (Figure 2 and [40, 41]). One line of research could investigate adapting enhanced window management techniques for 2D virtual desktops to this new scenario of a physical desktop, laptop, mouse, keyboard, and AR HMD. For example, researchers have proposed the ability to "peel back" windows to reveal what is underneath [12]; such peeling back could now be done in 3D, possibly from a physical screen into virtual AR space (Figure 4, left). Techniques for rapidly jumping around distant places [7] or bringing distal content close to the mouse cursor [5] could be applied. Documents and windows could be arranged in 3D piles, as has been proposed previously on 2D screens [1, 33]. Figure 4(right) shows a design for integrating virtual piles with a physical desk environment using a flagpole metaphor – the anchor point of these poles could be moved with a mouse or finger (without having to lift the hand into midair) and could also be used to access options related to each pile or floating window. "Time-machine computing" [38] allows a user to navigate back in time to see the contents of their 2D virtual desktop at a previous moment; this could be adapted to allow a user of AR to see the layout of virtual windows in their office on a previous day. Enhanced ways of accessing a file system could also be revived and integrated into new research prototypes, such as Presto's [11] ability to define folders whose content is dynamically updated in response to a query string. New interaction techniques could be designed to migrate windows and documents between a laptop's physical screen and the virtual display space provided by the AR HMD. 2D and 3D visualizations appearing in a physical screen or in virtual floating windows could be linked together in a manner similar to VisLink [9]. More research could be done around efficient placement of windows [31], possibly snapping to physical objects [35], and making it easy for a user to "pick up" all their virtual windows, "bring them along" while walking to another room [15], and have them automatically reposition themselves within a new physical office environment [14].

We can also observe that, as a user is surrounded by more floating content covering a larger angle, at some point, eye motions alone no longer suffice to switch between all such content, and rotations of the neck or torso become necessary, or even getting up and walking over to more distant windows. In other words, there comes a point when it would be more efficient to instead zoom in/out on content displayed within a smaller field-of-view, or cycle between overlapping windows all directly in front of the user. The tradeoff involved likely depends on the user's task (e.g., monitoring several information

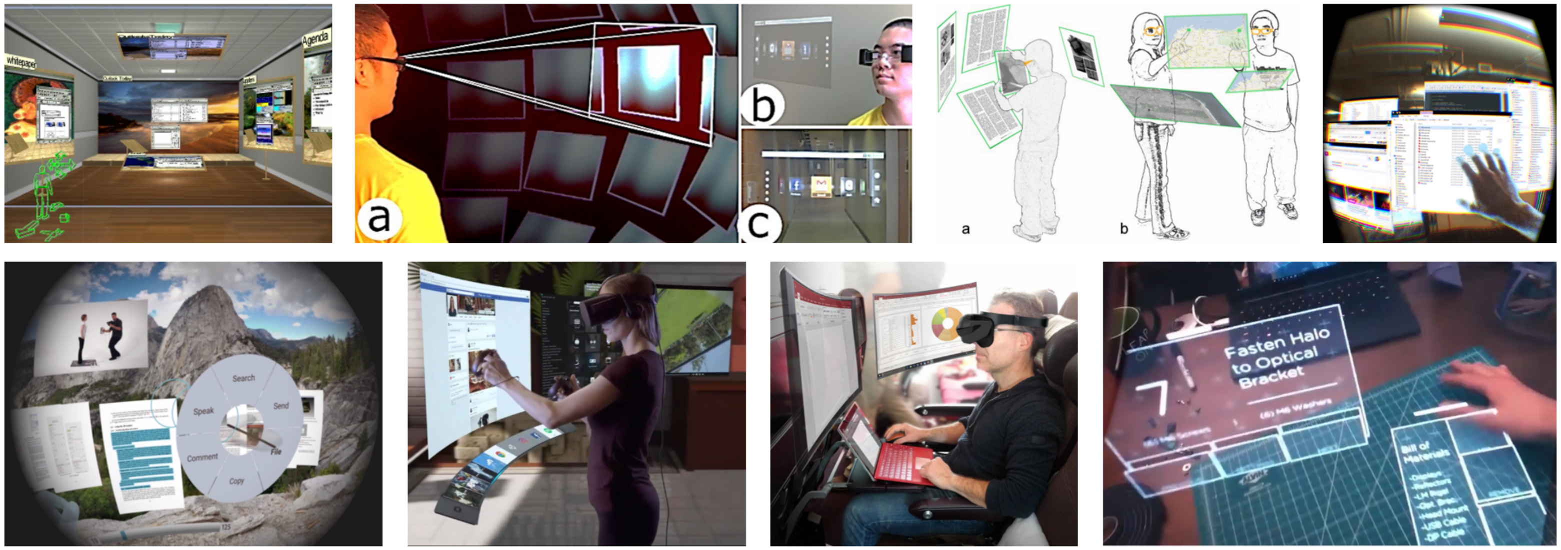

Figure 1: Surrounding a user with virtual windows. Top, left to right: Microsoft's Task Gallery [39], Personal cockpit [15], ethereal planes [13], Augmented Reality Workspace [6]. Bottom: prototype by Mike Alger [2], Oculus Dash [36], Office of the Future [19], Leap Motion's North Star [30].

sources versus dragging and dropping between windows). Although research related to this question has been done [20, 21, 24, 27, 32, 37], there is still no complete quantitative model of the tradeoff involved in displaying over a wider field-of-view versus zooming versus cycling through overlapping windows.

In addition to using an AR HMD with a laptop computer while seated, knowledge workers will also want to use the HMD to enhance their experience of using a smartphone when on the go (Figure 3). Although the HMD obviously allows for greater output space, it is less clear which kind of input (on the phone's touchscreen versus in midair) is best. Fingers can be tracked in midair by sensors on the headset, however such pointing suffers from hand tremor, fatigue, occlusions, difficulty sensing multi-touch gestures (such as mid-air pinch-to-zoom), and a lack of haptic feedback. Research will continue to investigate these issues.

To the extent that researchers hope for real-world adoption, it is instructive to consider the case of BumpTop [1]. BumpTop proposed advanced desktop interaction techniques including gestural-style interaction with a pen, the ability to define piles of documents, and simulated physics to encourage

Figure 3: Combining AR headsets with smartphones. Clockwise from top left: MultiFi [18], A scene from the short film "Lost Memories" [16], Spatial's exporting of a virtual note from a phone into AR [42], VESAD [34].

free-from layout and rearrangement of documents on the virtual desktop. It was first presented as a CHI paper, was spun off as a start-up company, and was featured as a TED talk. An online video demonstration of it has accumulated over 4 million views[4], and the beta software version was downloaded by the public "roughly 500k" times [Agarawala, personal communication]. The company was eventually sold to Google. Despite the clear interest and excitement around such an interaction paradigm, the source code was later released to the public by Google, and is no longer maintained by Google. Although it was highly influential (the CHI paper has been cited over 300 times), one of the reasons that BumpTop did not become a widely used product is that users do not actually spend much time on their virtual desktop — many laptop users spend most of their time working inside a web browser [Agarawala, personal communication].

Other ideas that have been proposed by researchers for enhancing window management or virtual desktops have seen very little adoption. Time-Machine Computing [38] is comparable to the "Task View" in Microsoft Windows 10, and Mac OS X offers Mission Control (formerly Dashboard, Exposé, and Spaces), however other ideas such as peelable windows or advanced file systems have not been

[4] http://www.youtube.com/watch?v=M0ODskdEPnQ

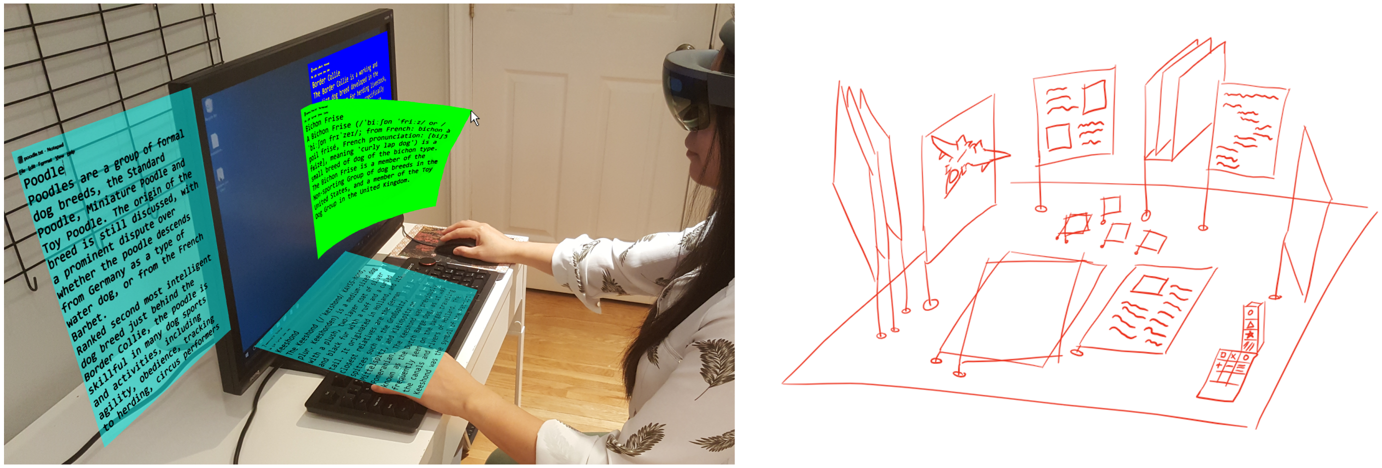

Figure 4: Left: a mockup of virtual windows that can be positioned outside, or peeled off of, a physical screen. Right: a sketch of virtual windows floating above a physical desktop, with virtual flagpoles connecting the virtual content to the physical surface. The anchor point of each flagpole could be moved using a mouse or direct touch, avoiding the need to raise the user's arm in mid-air.

adopted at all by major vendors. It is difficult or infeasible for 3rd party developers to modify the operating system or built-in window manager of Microsoft Windows or Mac OS, adding to the inertia of current interface paradigms.

Hence, to increase the chances of new UI paradigms being widely adopted, it would be useful for researchers to think about ways of integrating their prototypes with widely-used web-based apps (e.g., making services like Slack or Trello accessible within a prototype 3D window manager), as well as ways of working around the limitations of existing commercial OSs and windowing systems so that their prototypes can be used by the larger public. For example, to prototype ideas similar to those in Figure 3, a research team might develop a publicly-available app that runs on an AR HMD that recognizes the user's smartphone, and that displays shortcuts floating beside the user's phone, and/or documents or photos that the user has selected on their phone. Selecting a shortcut could cause the headset to send a signal to the phone to open an app, a webpage, or a document, and performing an appropriate action on the phone could cause a document or photo to be displayed in larger form by the HMD. Such a system could actually be deployed to the wider public as two apps (one for the phone and one for the headset), planting the seeds of new interaction possibilities in the minds of thousands of users, and perhaps influencing future versions of the OSs on smartphones and headsets.

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REFERENCES

[1] Anand Agarawala and Ravin Balakrishnan. 2006. Keepin' it real: pushing the desktop metaphor with physics, piles and the pen. In *ACM Conf. Human Factors in Computing Systems (CHI)*. 1283–1292.
[2] Mike Alger. 2015. VR Interface Design Pre-Visualisation Methods. https://vimeo.com/141330081
[3] Avegant. 2017. Introducing Avegant Light Field - Full Video. https://vimeo.com/212624616
[4] Ravin Balakrishnan, Thomas Baudel, Gordon Kurtenbach, and George Fitzmaurice. 1997. The Rockin' Mouse: integral 3D manipulation on a plane. In *ACM Conf. Human Factors in Computing Systems (CHI)*. 311–318.
[5] Patrick Baudisch, Edward Cutrell, Dan Robbins, Mary Czerwinski, Peter Tandler, Benjamin Bederson, Alex Zierlinger, et al. 2003. Drag-and-pop and drag-and-pick: Techniques for accessing remote screen content on touch-and pen-operated systems. In *Proc. INTERACT*, Vol. 3. 57–64.
[6] Raffi Bedikian. 2015. Under the Hood: The Leap Motion Hackathon's Augmented Reality Workspace. http://blog.leapmotion.com/hood-leap-motion-hackathons-augmented-reality-workspace/
[7] Olivier Chapuis and Nicolas Roussel. 2010. UIMarks: quick graphical interaction with specific targets. In *ACM Symp. User Interface Software and Technology (UIST)*. 173–182.
[8] Citi. 2016. Citi HoloLens Holographic Workstation. https://www.youtube.com/watch?v=0NogltmewmQ
[9] Christopher Collins and Sheelagh Carpendale. 2007. VisLink: Revealing relationships amongst visualizations. *IEEE Transactions on Visualization and Computer Graphics (TVCG)* 13, 6 (2007), 1192–1199.
[10] Stephen Di Verdi, Daniel Nurmi, and Tobias Hollerer. 2003. ARWin - a desktop augmented reality window manager. In *IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*.
[11] Paul Dourish, W Keith Edwards, Anthony LaMarca, and Michael Salisbury. 1999. Presto: an experimental architecture for fluid interactive document spaces. *ACM Transactions on Computer-Human Interaction (TOCHI)* 6, 2 (1999), 133–161.
[12] Pierre Dragicevic. 2004. Combining crossing-based and paper-based interaction paradigms for dragging and dropping between overlapping windows. In *ACM Symp. User Interface Software and Technology (UIST)*. 193–196.
[13] Barrett Ens, Juan David Hincapié-Ramos, and Pourang Irani. 2014. Ethereal planes: a design framework for 2D information space in 3D mixed reality environments. In *ACM Symp. Spatial User Interaction (SUI)*. 2–12.
[14] Barrett Ens, Eyal Ofek, Neil Bruce, and Pourang Irani. 2015. Spatial constancy of surface-embedded layouts across multiple environments. In *ACM Symp. Spatial User Interaction (SUI)*. 65–68.
[15] Barrett M Ens, Rory Finnegan, and Pourang P Irani. 2014. The personal cockpit: a spatial interface for effective task switching on head-worn displays. In *ACM Conf. Human Factors in Computing Systems (CHI)*. 3171–3180.
[16] François Ferracci. 2016. Lost Memories. https://youtu.be/9IVYU0Unw-Y
[17] Gartner. 2018. Hype Cycle for Emerging Technologies, 2018. https://www.gartner.com/smarterwithgartner/5-trends-emerge-in-gartner-hype-cycle-for-emerging-technologies-2018/
[18] Jens Grubert, Matthias Heinisch, Aaron Quigley, and Dieter Schmalstieg. 2015. MultiFi: Multi fidelity interaction with displays on and around the body. In *ACM Conf. Human Factors in Computing Systems (CHI)*. 3933–3942.
[19] Jens Grubert, Eyal Ofek, Michel Pahud, and Per Ola Kristensson. 2018. The Office of the Future: Virtual, Portable, and Global. *IEEE Computer Graphics and Applications (CG&A)* 38, 6 (2018), 125–133.

[20] Yves Guiard, Michel Beaudouin-Lafon, Julien Bastin, Dennis Pasveer, and Shumin Zhai. 2004. View size and pointing difficulty in multi-scale navigation. In *Proc. Advanced visual interfaces (AVI)*. ACM, 117–124.

[21] Carl Gutwin, Andy Cockburn, and Ashley Coveney. 2017. Peripheral Popout: The Influence of Visual Angle and Stimulus Intensity on Popout Effects. In *ACM Conf. Human Factors in Computing Systems (CHI)*. 208–219.

[22] Juan David Hincapié-Ramos, Xiang Guo, Paymahn Moghadasian, and Pourang Irani. 2014. Consumed endurance: a metric to quantify arm fatigue of mid-air interactions. In *ACM Conf. Human Factors in Computing Systems (CHI)*. 1063–1072.

[23] Fu-Chung Huang, Kevin Chen, and Gordon Wetzstein. 2015. The light field stereoscope: immersive computer graphics via factored near-eye light field displays with focus cues. *ACM Transactions on Graphics (TOG)* 34, 4 (2015), 60.

[24] Mikkel R Jakobsen and Kasper Hornbæk. 2013. Interactive visualizations on large and small displays: The interrelation of display size, information space, and scale. *IEEE Transactions on Visualization and Computer Graphics (TVCG)* 19, 12 (2013), 2336–2345.

[25] Sujin Jang, Wolfgang Stuerzlinger, Satyajit Ambike, and Karthik Ramani. 2017. Modeling cumulative arm fatigue in mid-air interaction based on perceived exertion and kinetics of arm motion. In *ACM Conf. Human Factors in Computing Systems (CHI)*. 3328–3339.

[26] Kangsoo Kim, Mark Billinghurst, Gerd Bruder, Henry Been-Lirn Duh, and Gregory F Welch. 2018. Revisiting Trends in Augmented Reality Research: A Review of the 2nd Decade of ISMAR (2008–2017). *IEEE Transactions on Visualization and Computer Graphics (TVCG)* (2018).

[27] Naohiro Kishishita, Kiyoshi Kiyokawa, Jason Orlosky, Tomohiro Mashita, Haruo Takemura, and Ernst Kruijff. 2014. Analysing the effects of a wide field of view augmented reality display on search performance in divided attention tasks. In *IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 177–186.

[28] Gregory Kramida. 2016. Resolving the vergence-accommodation conflict in head-mounted displays. *IEEE Transactions on Visualization and Computer Graphics (TVCG)* 1 (2016), 1–1.

[29] Bernard Kress. 2019. AR/VR/MR: Meeting the optical design challenges. https://www.electrooptics.com/analysis-opinion/arvrmr-meeting-optical-design-challenges

[30] Leap Motion. 2018. Project North Star: Desk UI. https://www.youtube.com/watch?v=6dB1IRg3Qls

[31] Joon Hyub Lee, Sang-Gyun An, Yongkwan Kim, and Seok-Hyung Bae. 2018. Projective Windows: Bringing Windows in Space to the Fingertip. In *ACM Conf. Human Factors in Computing Systems (CHI)*.

[32] Can Liu, Olivier Chapuis, Michel Beaudouin-Lafon, Eric Lecolinet, and Wendy E Mackay. 2014. Effects of display size and navigation type on a classification task. In *ACM Conf. Human Factors in Computing Systems (CHI)*. 4147–4156.

[33] Richard Mander, Gitta Salomon, and Yin Yin Wong. 1992. A 'pile' metaphor for supporting casual organization of information. In *ACM Conf. Human Factors in Computing Systems (CHI)*. 627–634.

[34] Erwan Normand and Michael J McGuffin. 2018. Enlarging a Smartphone with AR to Create a Handheld VESAD (Virtually Extended Screen-Aligned Display). In *IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 123–133.

[35] Benjamin Nuernberger, Eyal Ofek, Hrvoje Benko, and Andrew D Wilson. 2016. SnapToReality: Aligning augmented reality to the real world. In *ACM Conf. Human Factors in Computing Systems (CHI)*.

[36] Oculus. 2017. Introducing Oculus Dash. https://www.youtube.com/watch?v=SvP_RI_S-bw

[37] Matthew D Plumlee and Colin Ware. 2006. Zooming versus multiple window interfaces: Cognitive costs of visual comparisons. *ACM Transactions on Computer-Human Interaction (TOCHI)* 13, 2 (2006), 179–209.

[38] Jun Rekimoto. 1999. Time-machine computing: a time-centric approach for the information environment. In *ACM Symp. User Interface Software and Technology (UIST)*. 45–54.

[39] George Robertson, Maarten Van Dantzich, Daniel Robbins, Mary Czerwinski, Ken Hinckley, Kirsten Risden, David Thiel, and Vadim Gorokhovsky. 2000. The Task Gallery: a 3D window manager. In *ACM Conf. Human Factors in Computing Systems (CHI)*.

[40] Marcos Serrano, Barrett Ens, Xing-Dong Yang, and Pourang Irani. 2015. Desktop-Gluey: augmenting desktop environments with wearable devices. In *Proc. Int. Conf. Human-Computer Interaction with Mobile Devices and Services Adjunct*. ACM, 1175–1178.

[41] Marcos Serrano, Barrett Ens, Xing-Dong Yang, and Pourang Irani. 2015. Gluey: Developing a head-worn display interface to unify the interaction experience in distributed display environments. In *Proc. Int. Conf. Human-Computer Interaction with Mobile Devices and Services (MobileHCI)*. ACM, 161–171.

[42] Spatial. 2018. Spatial - Collaborate from Anywhere in AR. https://www.youtube.com/watch?v=PG3tQYlZ6JQ

[43] @spatialxr. 2018. Tweet. https://twitter.com/spatialxr/status/1055083141524848646