Gaze-aware Displays and Interaction

By

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Sample Course Notes
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Abstract

Being able to detect and to employ gaze enhances digital displays. Research on gaze-contingent or gaze-aware display devices dates back two decades. This is the time, though, that it could truly be employed for fast, low-latency gaze-based interaction and for optimization of computer graphics rendering such as in foveated rendering. Moreover, Virtual Reality (VR) is becoming ubiquitous. The widespread availability of consumer grade VR Head Mounted Displays (HMDs) transformed VR to a commodity available for everyday use. VR applications are now abundantly designed for recreation, work and communication. However, interacting with VR setups requires new paradigms of User Interfaces (UIs), since traditional 2D UIs are designed to be viewed from a static vantage point only, e.g. the computer screen. Adding to this, traditional input methods such as the keyboard and mouse are hard to manipulate when the user wears a HMD. Recently, companies such as HTC announced embedded eye-tracking in their headsets and therefore, novel, immersive 3D UI paradigms embedded in a VR setup can now be controlled via eye gaze. Gaze-based interaction is intuitive and natural the users. Tasks can be performed directly into the 3D spatial context without having to search for an out-of-view keyboard/mouse. Furthermore, people with physical disabilities, already depending on technology for recreation and basic communication, can now benefit even more from VR. This course presents timely, relevant information on how gaze-contingent displays, in general, including the recent advances of Virtual Reality (VR) eye tracking capabilities can leverage eye-tracking data to optimize the user experience and to alleviate usability issues surrounding intuitive interaction challenges. Research topics to be covered include saliency models, gaze prediction, gaze tracking, gaze direction, foveated rendering, stereo grading and 3D User Interfaces (UIs) based on gaze on any gaze-aware display technology.

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Introduction

Being able to detect and to employ gaze enhances digital displays. Research on gaze-contingent or gaze-aware display devices dates back two decades. This is the time, though, that it could truly be employed for fast, low-latency gaze-based interaction and for optimization of computer graphics rendering such as in foveated rendering. Moreover, Virtual Reality (VR) is becoming ubiquitous. The widespread availability of consumer grade VR Head Mounted Displays (HMDs) transformed VR to a commodity available for everyday use. VR applications are now abundantly designed for recreation, work and communication. However, interacting with VR setups requires new paradigms of User Interfaces (UIs), since traditional 2D UIs are designed to be viewed from a static vantage point only, e.g. the computer screen. Adding to this, traditional input methods such as the keyboard and mouse are hard to manipulate when the user wears a HMD. Recently, companies such as HTC announced embedded eye-tracking in their headsets and therefore, novel, immersive 3D UI paradigms embedded in a VR setup can now be controlled via eye gaze. Gaze-based interaction is intuitive and natural the users. Tasks can be performed directly into the 3D spatial context without having to search for an out-of-view keyboard/mouse. Furthermore, people with physical disabilities, already depending on technology for recreation and basic communication, can now benefit even more from VR. This course presents timely, relevant information on how gaze-contingent displays, in general, including the recent advances of Virtual Reality (VR) eye tracking capabilities can leverage eye-tracking data to optimize the user experience and to alleviate usability issues surrounding intuitive interaction challenges. Course topics to be covered include saliency models, gaze prediction, gaze tracking, gaze direction, foveated rendering, stereo grading and 3D User Interfaces (UIs) based on gaze on any gaze-aware display technology.

1.1 Motivation

Gaze-aware displays, in general, including several Head Mounted Displays (HMDs) with integrated eye tracking have recently hit the market. For gaze-aware displays to prove useful, it is essential that the community has an understanding of how eye tracking measurements should be recorded, analyzed, and reported as well as how gaze contingent displays could be exploited for rendering as well as for interaction. It is also critical that the community can take advantage of built-in eye tracking to advance Immersive Virtual Environments using novel techniques such as gaze direction, gaze tracking, stereo grading, foveated rendering, and beyond.

1.2 Target Audience

The target audience for this course is researchers interested in gaze-aware displays either in relation to gaze prediction or applying eye-tracking in Virtual Reality. This course represents a birds-eye view of research on gaze prediction, eye-movements, eye-tracking, data capture and analysis, and state-of-the-art applications of eye-tracking in VR and beyond. Those wishing to grasp the theory and practice of gaze-contingent displays will all benefit from this course.

1.3 Course Overview

Gaze-aware displays exploit gaze information either for optimization of rendering or as a means for interaction. The integration of eye-tracking and VR reveals where the user focuses their attention. Content creators and world builders can exploit this information for gaze direction and interaction as well as alleviate motion sickness through stereo grading so that the VR experience is comfortable, safe and effective for the user. This course provides the necessary background and overview to be acquainted with gaze-aware displays towards establishing gaze tracking as an industry standard.

1.4 Course Outline

1. Welcome and Overview
2. Gaze Prediction
3. Gaze Tracking
4. Gaze Direction
5. Foveated Rendering
6. Virtual Environments and Eye Tracking (including an overview of hardware available)
7. Special Considerations for Eye Tracking in Virtual Environments
8. Summary and Future Directions
9. Questions from the Audience

1.5 Course Speaker Bio: Katerina Mania

Katerina Mania serves as an Associate Professor at the School of Electrical and Computer Engineering, Technical University of Crete, Greece after research positions at HP Labs, UK where she worked on Web3D and University of Sussex, UK where she served as an Assistant Professor in Multimedia Systems. She received her BSc in Mathematics from the University of Crete, Greece and her MSc and PhD in Computer Science from the University of Bristol, UK. Her primary research interests integrate perception, vision and neuroscience to optimise computer graphics rendering and VR technologies with current focus on gaze-contingent displays. She has co-chaired technical programs and has participated in over 100 international conference program committees. She serves as one of the Associate Editors for Presence, Tele-operators and Virtual Environments (MIT Press) and ACM Transactions on Applied Perception.

1.6 Course Speaker Bio: Ann McNamara

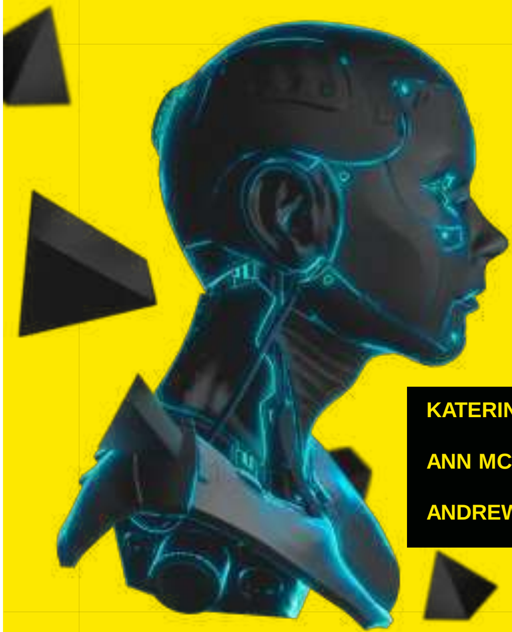
Ann McNamara is an Associate professor in the Department of Visualization at Texas A&M University. Her research focuses on novel approaches for optimizing an individual's experience when creating, viewing and interacting with virtual and augmented spaces. She is the recipient of an NSF CAREER AWARD entitled "Advancing Interaction Paradigms in Mobile Augmented Reality using Eye Tracking". This project investigates how mobile eye tracking, which monitors where a person is looking while on the go, can be used to determine what objects in a visual scene a person is interested in, and thus might like to have annotated in their augmented reality view. In 2019, she was named as one of twenty-one Presidential Impact Fellows at Texas A&M University.

1.7 Course Speaker Bio: Andrew Polychronakis

Andrew Polychronakis is a researcher and PhD candidate at the School of Electrical and Computer Engineering, Technical University of Crete, Greece. His thesis focused on foveated rendering proposing an innovative ray-tracing rendering pipeline for which foveated rendering is applied. Acceleration of path tracing reduces the total numbers of rays at the generation process.

2

Course Slide Deck



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GAZE-AWARE DISPLAYS AND INTERACTION

KATERINA MANIA, TECHNICAL UNIVERSITY OF CRETE, GREECE

ANN MCNAMARA, TEXAS A&M, USA

ANDREW POLYCHRONAKIS, TECHNICAL UNIVERSITY OF CRETE, GREECE

COURSE SCHEDULE

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- **Welcome and Overview**
- **Gaze Prediction, Gaze Tracking, Gaze Direction, Stereo grading, Gaze-based UIs [Katerina Mania]**
- **Foveated Rendering [Andrew Polychronakis]**
- **Virtual Environments and Eye Tracking (including an overview of hardware available). Special Considerations for Eye Tracking in Virtual Environments [Ann McNamara]**
- **Questions from the Audience [ALL]**

GAZE PREDICTION, TRACKING, DIRECTION, STEREO GRADING, UIS

KATERINA MANIA

TECHNICAL UNIVERSITY OF CRETE, GREECE

OVERVIEW

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- **Gaze prediction**
- **Gaze direction**
- **3D Uis based on gaze**
- **Stereo grading**
- **Conclusions**

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GAZE PREDICTION

LOW-LEVEL, TASK-BASED, HIGH-LEVEL SALIENCY

GAZE PREDICTION MODELS

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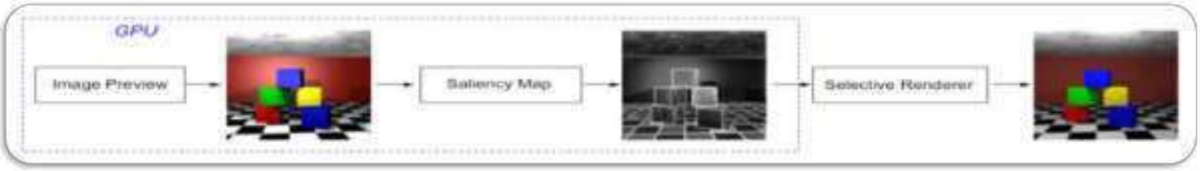
- **Gaze prediction** can **accelerate image synthesis** by reducing computation on non-attended scene regions
- Controlling **the level of detail in geometric models** (Zotos et al 2009)
- Gaze Prediction of saccades landing positions **to reduce system latency** (Arabadzhiyska et al 2017)
- Saliency models **select the best views to scan** indoor scenes in order to produce 3D models (Xu et al 2016)
- High level saliency models **to optimize an LOD manager** based on predicted gaze on objects on mobile platforms (Koulieris et al. 2014)
- Automated high level **saliency prediction of game balancing** (Koulieris et al 2014)
- Predicting **tactile mesh saliency** (Lau et al 2016)
- **Eye tracking-based, low-level, high-level, task-based**

LOW-LEVEL ATTENTION-AWARE APPLICATIONS

LEVEL-OF-DETAIL

FIT-guided selective rendering

- **FIT-based selective rendering, important parts rendered in high quality, remaining areas rendered at lower quality**



Images from Longhurst, P., Debattista, K., & Chalmers, A. (2006, January). A gpu based saliency map for high-fidelity selective rendering. In *Proceedings of the 4th international conference on Computer graphics, virtual reality, visualisation and interaction in Africa* (pp. 21-29).

SIMULATING GAZE BEHAVIOR

CHARACTERS AND CROWDS

Simulating gaze behavior

Extracting scene interest points

Image from Grillon, H., & Thalmann, D. (2009). Simulating gaze attention behaviors for crowds. *Computer Animation and Virtual Worlds*, *20*(2-3), 111-119.

TASK-RELATED SALIENCY

COMBINING TASK-BASED METHODS AND LOW LEVEL FEATURES

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Low level & task-based and goal-directed methods

- **Saliency models and task related data linearly combined** to track visually attended objects in a VE
- **Demonstrating how the visual attention tracking framework can be applied to managing the level of details in VEs**

Image from Hillaire, S., Lecuyer, A., Regia-Corte, T., Cozot, R., Royan, J., & Breton, G. (2010, November). A real-time visual attention model for predicting gaze point during first-person exploration of virtual environments. In *Proceedings of the 17th acm symposium on virtual reality software and technology* (pp. 191-198).

Navigation in VR

MACHINE LEARNING APPROACHES

IMPLICIT MODELING OF HIGH LEVEL EFFECTS

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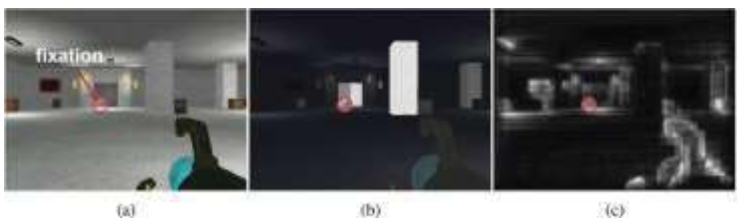
Gaze Prediction Heuristics for 3D Action Games - Machine Learning on eye tracking data

- **Machine learning techniques applied to eye tracking** data to train a saliency detection model for pre-defined sets of static photographs (judd et al. 2009)
- Importance map scoring gaze amount on objects, then as heuristic to predict gaze (Bernhard 2010)
- **for 3D Action Games**

  Visually highlighting important objects (b) not just salient pixels (c)



Images from Bernhard, M., Stavrakis, E., & Wimmer, M. (2010). An empirical pipeline to derive gaze prediction heuristics for 3D action games. *ACM Transactions on Applied Perception (TAP)*, *8*(1), 1-30

HIGH LEVEL SALIENCY

MAPPING VISUAL REPRESENTATIONS TO MEANING AND SEMANTICS

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A High Level Saliency Predictor

- **The goal is to define a computational model applicable to any context; a challenging task**
- When attending a scene, recently acquired knowledge from attentional processing **is combined with pre-existing knowledge** about a context, e.g. "bedroom"
- Attentional processing via Gaussian combination rules. Every object in the scene has a set of bayesian priors on the areas that the object is expected to be attended
- The chimney **high probability of attendance** on the top roof, low in other areas
- high level saliency guides attention and weights of each hypothesis are derived so that the model is calibrated
- **The posterior probability is calculated that the viewer will fixate on an object independent of task**

Images from Koulieris, G. A., Drettakis, G., Cunningham, D., & Mania, K. (2014). An automated high-level saliency predictor for smart game balancing. *ACM Transactions on Applied Perception (TAP)*, *11*(4), 1-21

HSLM - THE HIGH LEVEL SALIENCY MODELER

GPU BASED IMPLEMENTATION

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Implementation

- **Estimates in real time a posterior probability term of attendance** in a shader, based on viewpoint, i.e. an object may or may not appear as singleton depending on the viewpoint
- Identifies objects expected to attract attention

High Level Saliency

Low Level Saliency

Images from Koulieris, G. A., Drettakis, G., Cunningham, D., & Mania, K. (2014). An automated high-level saliency predictor for smart game balancing. *ACM Transactions on Applied Perception (TAP)*, *11*(4), 1-21.

EVALUATION OF GAME LEVEL EDITING

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GAME BALANCING - EYE-TRACKING DATA HEAT MAPS

Game Level Editing

- **Looking for an object is a common task in (Action-)Adventure video games**
- Plot-critical objects are placed in selected locations to ease or burden the player
- **Maintain challenge Aid game level designer to identify object saliency depending on location**

Aggregated fixations over raw eye data from all participants and visual angles

Images from Koulieris, G. A., Drettakis, G., Cunningham, D., & Mania, K. (2014). An automated high-level saliency predictor for smart game balancing. *ACM Transactions on Applied Perception (TAP)*, *11*(4), 1-21.

LOD FOR MOBILE GRAPHICS

Koulieris et al. 2014

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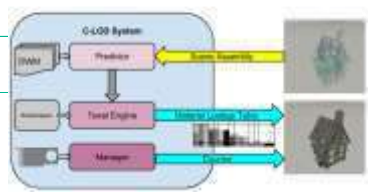
C-LOD FOR UNITY 3D™

High Level Saliency and Rendering



- Reactive fixed frame rate scheduler based on attention
- **C-LOD lowers the rendering quality of objects predicted not to be attended**
- The highest quality is maintained for all attended objects

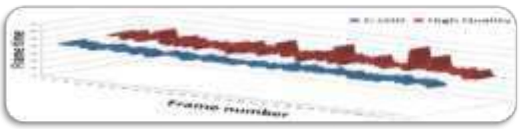
Three complex effects usually omitted in mobile devices as they require many texture fetches were selected

Subsurface scattering *Refraction* *Bump Mapping*

Images from Koulieris, G. A., Drettakis, G., Cunningham, D., & Mania, K. (2014, July). C-LOD: Context-aware material level-of-detail applied to mobile graphics. In *Computer Graphics Forum* (Vol. 33, No. 4, pp. 41-49).

LOD FOR MOBILE GRAPHICS

C-LOD FOR UNITY 3D™



Images from Koulieris, G. A., Drettakis, G., Cunningham, D., & Mania, K. (2014, July). C-LOD: Context-aware material level-of-detail applied to mobile graphics. In *Computer Graphics Forum* (Vol. 33, No. 4, pp. 41-49).

HOW DO PEOPLE EXPLORE VIRTUAL ENVIRONMENTS?

- Capture and analysis of gaze and head orientation data of 169 users exploring stereoscopic, **static omni-directional panoramas**
- Applications include **Automatic thumbnailing**, **Compression in non-salient areas**, **Automatic allignment of cuts in vr video**

Automatic alignment of cuts in VR video

Images from Sitzmann, V., Serrano, A., Pavel, A., Agrawala, M., Gutierrez, Wetzstein, G. (2018). Saliency in VR: How do people explore virtual environments?. *IEEE transactions on visualization and computer graphics*, *24*(4), 1633-1642.

SACCADE LANDING POSITION FOR GAZE-CONTIGENT RENDERING

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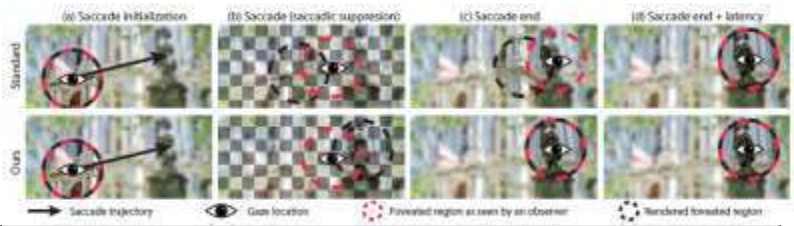
- Collecting saccades samples. A **computational model based on ballistic trajectories captures their characteristics**
- **Velocity method to detect end/start of saccade when velocity drops below a threshold**
- VR problems, movement of headset, loss of gaze direction, quality of the screen



Validation: reducing delay in gaze-contingent rendering user experience

Images from Arabadzhiyska, E., Tursun, O. T., Myszkowski, K., Seidel, H. P., & Didyk, P. (2017). Saccade landing **Images from** position prediction for gaze-contingent rendering. *ACM Transactions on Graphics (TOG)*, *36*(4), 1-12

TACTILE MESH SALIENCY

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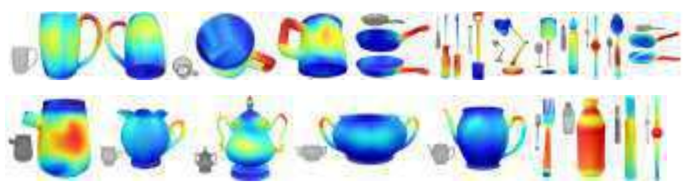
- **Tactile saliency** -- salient points on A 3D MESH THAT A HUMAN LIKELY TO **GRASP**, **PRESS** OR **TOUCH**
- Representing a 3D shape with **multiple depth images**
- **A deep neural network that maps a patch to a saliency value for the patch center**

Grasp saliency map, top training data, bottom output



Images from Lau, M., Dev, K., Shi, W., Dorsey, J., & Rushmeier, H. (2016). Tactile mesh saliency. *ACM Transactions on Graphics (TOG)*, *35*(4), 1-11

TACTILE MESH SALIENCY -- APPLICATIONS

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- **Fabrications material suggestion papercraft**. The more likely a surface point will be touched, the more sturdy the paper can be not to break
- **Fabrications material suggestion** the more likely a surface point will be grasped, the softer **the 3D printed material** can be so comfortable to grasp
- **Rendering properties suggestion** (such as shininess and ambience properties) of 3d shapes based on the computed saliency values

Screwdriver, 6 discreet parts and materials

Images from Lau, M., Dev, K., Shi, W., Dorsey, J., & Rushmeier, H. (2016). Tactile mesh saliency. *ACM Transactions on Graphics (TOG)*, *35*(4), 1-11

MESH SALIENCY VIA SPECTRAL PROCESSING

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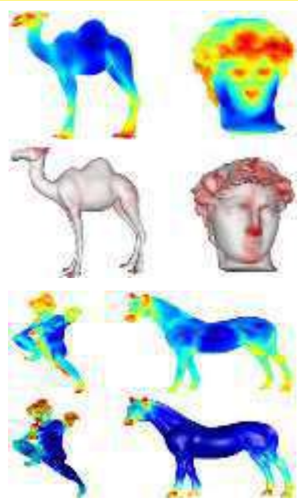
Top spectral
Eyes nose mouth



- Perceptually-based measure of the importance of a local region on a 3D surface mesh
- **Incorporating global considerations by making use of spectral attributes of the mesh**, unlike methods on **local** geometry
- The **log- Laplacian spectrum of the mesh** are frequencies showing differences from expected behaviour capturing saliency in the **frequency domain**
- **Information about frequencies in the spatial domain** at multiple spatial scales to localise salient features -- output final global salient areas

Images from Song, R., Liu, Y., Martin, R. R., & Rosin, P. L. (2014). Mesh saliency via spectral processing. *ACM Transactions On Graphics (TOG)*, *33*(1), 1-17.

George Leifman, Elizabeth Shtrom, and Ayellet Tal. 2012. Surface regions of interest for viewpoint selection. In Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR'12). 414--421

Top spectral
Eyes and feet

3D ATTENTION-DRIVEN DEPTH ACQUISITION FOR OBJECTS IDENTIFICATION

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- **Reconstructing the scene while online** identifying the objects from among a large collection of 3D shapes
- **A 3D Attention Model selects the best views and informative regions to scan from** in each view to focus on, to achieve efficient object recognition
- **The effectiveness is demonstrated on an autonomous robot (PR)** that explores a scene and identifies the objects to construct a 3D scene model

Depth camera on robot Scanned, object identified from 3D database, driven by attention, retrieval of 3D models

Images from Xu, K., Shi, Y., Zheng, L., Zhang, J., Liu, M., Huang, H., ... & Chen, B. (2016). 3D attention-driven depth acquisition for object identification. *ACM Transactions on Graphics (TOG)*, *35*(6), 1-14.

3D ATTENTION-DRIVEN DEPTH ACQUISITION FOR OBJECTS IDENTIFICATION

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Acquired depth images, identification, attention, output

- **Reconstructing the scene while** identifying objects from database
- 3D Attention Model for object identification
- **The first level selects the next-best-views (NBVs)** for depth
- **The second concentrates on the most discriminative regions**

Images from Xu, K., Shi, Y., Zheng, L., Zhang, J., Liu, M., Huang, H., ... & Chen, B. (2016). 3D attention-driven depth acquisition for object identification. *ACM Transactions on Graphics (TOG)*, *35*(6), 1-14.

CNN-BASED GAZE PREDICTION IN DYNAMIC SCENES

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Acquired depth images, identification, attention, output

- **Analyses of users' gaze behaviors in dynamic virtual scenes**
- **A CNN-based model (DGaze) that combines object position sequence, head velocity sequence, and saliency features to predict users' gaze positions.**
- **Also, predicting future gaze positions with higher precision by combining accurate past gaze data gathered using an eye tracker**

Images from Z. Hu, S. Li, C. Zhang, K. Yi, G. Wang and D. Manocha, "DGaze: CNN-Based Gaze Prediction in Dynamic Scenes," in *IEEE Transactions on Visualization and Computer Graphics*, vol. 26, no. 5, pp. 1902-1911, May 2020, doi: 10.1109/TVCG.2020.2973473.

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GAZE DIRECTION

MANIPULATING ATTENTION IN COMPUTER GAMES

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LOW-LEVEL-BASED GUIDING PRINCIPLES

In-game advertising

- **A frequently searched game object is modified to share perceptual features with a target item.**
- **increasing the saliency of advertising billboards by designing task-relevant objects**
- Requires manual 3D-model modifications

Memory task, task-relevant positioning and appearance

Images from Bernhard, M., Zhang, L., & Wimmer, M. (2011, June). Manipulating attention in computer games. In *2011 IEEE 10th IVMSP Workshop: Perception and Visual Signal Analysis* (pp. 153-158). IEEE.

SUBTLE GAZE GUIDANCE

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Subtle gaze guidance requires altering the visible scene context - subtly

- **Steering attention** to a specified target location, which can significantly differ from **the natural fixation location**

Images from McNamara, A., Bailey, R., & Grimm, C. (2009). Search task performance using subtle gaze direction with the presence of distractions. *ACM Transactions on Applied Perception (TAP)*, *6*(3), 1-19.

SUBTLE GAZE GUIDANCE

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Subtle gaze guidance requires altering the visible scene context - subtly

- **Presenting brief warm-cool modulations** to the peripheral field of view, **draws the foveal vision** to the modulated region

Images from McNamara, A., Bailey, R., & Grimm, C. (2009). Search task performance using subtle gaze direction with the presence of distractions. *ACM Transactions on Applied Perception (TAP)*, *6*(3), 1-19.

SUBTLE GAZE GUIDANCE

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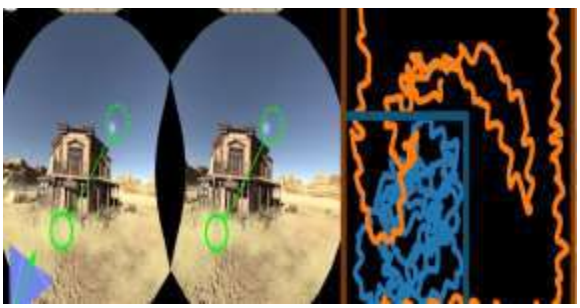
Subtle gaze direction in immersive environments



- **Subtle gaze direction** for wide field of view scenarios in **immersive environments**, gaze guidance for **redirected walking in VR**

Grogorick et al, 2017, Langbehn et al., 2018
Images from Sun, Q., Patney, A., Wei, L. Y., Shapira, O., Lu, J., Asente, P., ... & Kaufman, A. (2018). Towards virtual reality infinite walking: dynamic saccadic redirection. *ACM Transactions on Graphics (TOG)*, *37*(4), 1-13.

LOOK OVER HERE: ATTENTION-DIRECTING COMPOSITION OF MANGA ELEMENTS

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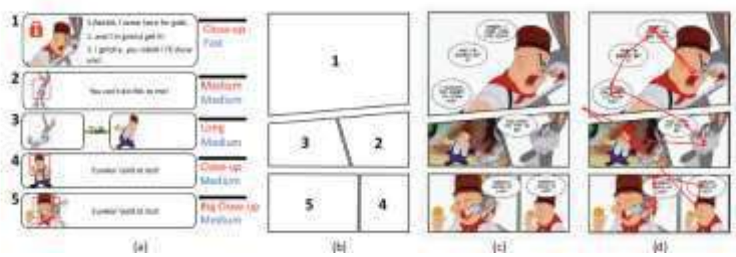

Shot type (red text), motion state (blue text), red rectangles ROIs

- THE TRAINING SET IS ANNOTATED (SUBJECTS/BALLONS) **AND COLLECT READERS' EYE GAZE**
- A COMPOSITION IS CREATED **INTERACTIVELY**, WHERE THE LEARNED PROBABILISTIC MODEL IS USED TO GENERATE A GALLERY OF COMPOSITION SUGGESTIONS, IN RESPONSE TO USER-PROVIDED HIGH-LEVEL SPECIFICATION
- THE USER GIVES **THE NUMBER OF PANELS THE SHOT TYPE AND MOTION STATE**

Images from Cao, Y., Lau, R. W., & Chan, A. B. (2014). Look over here: Attention-directing composition of manga elements. *ACM Transactions on Graphics (TOG)*, *33*(4), 1-11.

DIRECTING USER ATTENTION VIA VISUAL FLOW ON WEB DESIGNS

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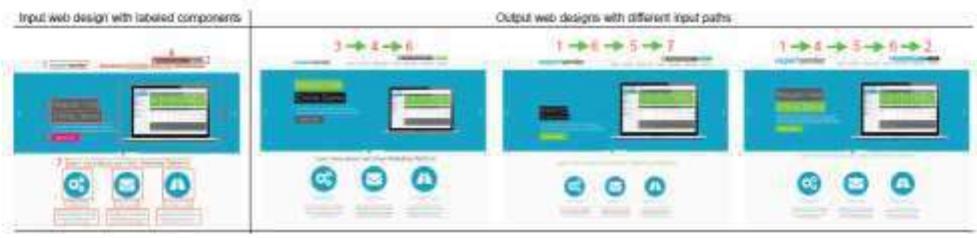
To increase the prob. of eyes transiting from1 to 6, 3 and 4 are made smaller and text away from 1



- USER ATTENTION MODELS PRODUCE OPTIMIZED WEB DESIGNS
- **THE WEB DESIGN IS OPTIMIZED AUTOMATICALLY TO MATCH DESIGNER'S INTENT**
- THE ATTENTION TERM ENCOURAGES USERS' ATTENTION **TO MATCH DESIGNERS' INTENDED VISUAL FLOW.** THE REGULARIZATION AND PRIOR TERMS IMPOSE **DESIGN PRINCIPLES**

Images from Pang, X., Cao, Y., Lau, R. W., & Chan, A. B. (2016). Directing user attention via visual flow on web designs. *ACM Transactions on Graphics (TOG)*, *35*(6), 1-11

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STEREO GRADING

GAZE PREDICTION USING MACHINE LEARNING FOR GAMES

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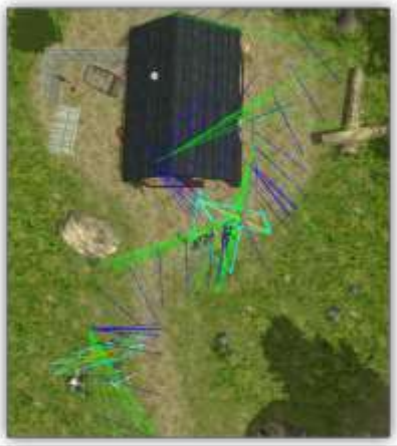
Manipulating stereo content for comfortable viewing, a process called stereo grading
Player actions are highly correlated with the present state of a game (game variables)

1. **Real-time gaze prediction based on Decision Forests without manual object tagging**
2. Dynamic, **comfortable** stereo grading **without cardboarding effects**
3. Account for task, learn from gaze data

Images from Koulieris, G. A., Drettakis, G., Cunningham, D., & Mania, K. (2016, March). Gaze prediction using machine learning for dynamic stereo manipulation in games. In *2016 IEEE Virtual Reality (VR*

ATTENTION MODEL

3-STEP PROCEDURE



Identify important game variables and object classes

↓

Data Collection

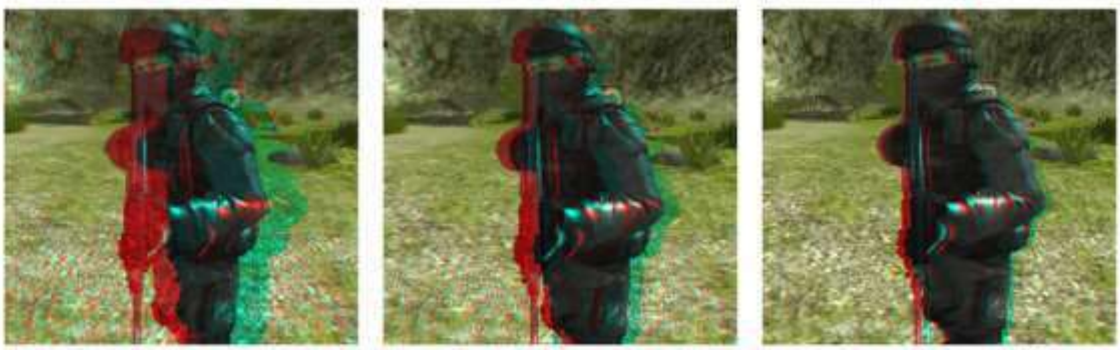
↓

Classifier Training

Images from Koulieris, G. A., Drettakis, G., Cunningham, D., & Mania, K. (2016, March). Gaze prediction using machine learning for dynamic stereo manipulation in games. In *2016 IEEE Virtual Reality (VR*

GAZE-BASED DYNAMIC STEREO GRADING

EXAMPLES



No display management — Ours — OSCAM

Left to right: No display management, Ours, OSCAM. Please use red/cyan anaglyph glasses; best viewed on a monitor.

Images from Koulieris, G. A., Drettakis, G., Cunningham, D., & Mania, K. (2016, March). Gaze prediction using machine learning for dynamic stereo manipulation in games. In *2016 IEEE Virtual Reality*

GAZESTEREO3D: SEAMLESS DISPARITY MANIPULATIONS

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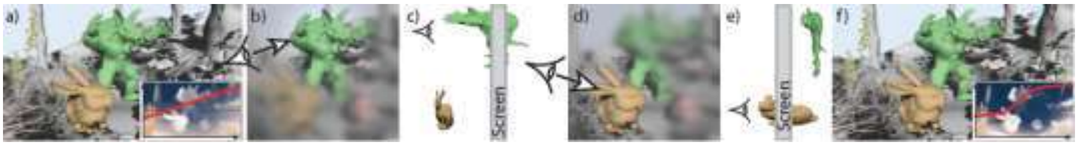
Modifying disparity of attended objects, seamless transition between them



Applying gradual depth adjustments at eye fixation, so that they remain unnoticeable

- **A REAL-TIME CONTROLLER THAT APPLIES LOCAL MANIPULATIONS TO STEREOSCOPIC CONTENT**
- **IMPROVEMENTS IN DEPTH PERCEPTION WITHOUT SACRIFICING VISUAL QUALITY**
- TO ENHANCE PERCEIVED DEPTH THE METHOD **EXPANDS ITS RANGE AROUND THE FIXATION LOCATION** AND **REDUCES IT IN UNATTENDED REGIONS**
- **OBJECTS** AROUND FIXATION **ARE MOVED TOWARDS THE SCREEN** TO REDUCE DISCOMFORT

Images from Kellnhofer, P., Didyk, P., Myszkowski, K., Hefeeda, M. M., Seidel, H. P., & Matusik, W. (2016). GazeStereo3D: Seamless disparity manipulations. *ACM Transactions on Graphics (TOG)*, *35*(4), 1-13.

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GAZE-DRIVEN USER INTERFACES

GAZE-BASED USER INTERFACES

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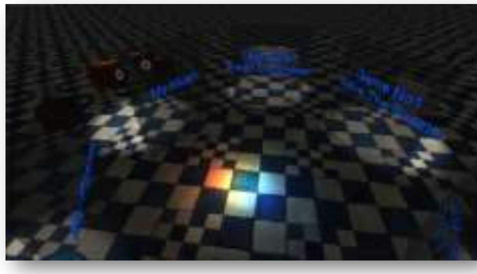
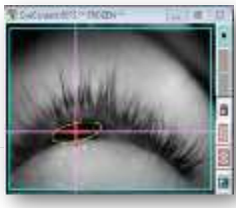
- **A 3D MULTIMEDIA USER INTERFACE BASED ON EYE-TRACKING**
- EYE GAZE DATA COULD ALSO SIMULATE THE MOUSE CLICK BY DETECTING BLINKS
- **MIDAS' TOUCH & VIEWPOINT SETTINGS**
- REPLACE WITH SINGLE BUTTON
  - SPACE KEY OR HEAD TRACKER DATA



Images from Sidorakis, N., Koulieris, G. A., & Mania, K. (2015, March). Binocular eye-tracking for the control of a 3D immersive multimedia user interface. In *2015 IEEE 1St workshop on everyday virtual reality (WEVR)* (pp. 15-18). IEEE.



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HCI SYSTEM BASED ON MULTIMODAL GAZE TRACKING

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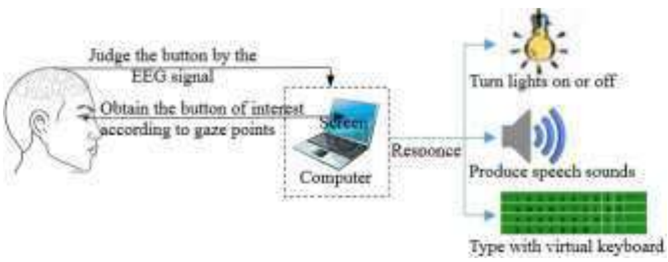

- **LIS PATIENTS EFFECTIVELY COMMUNICATING WITH THE OUTSIDE**
- **THE SYSTEM GETS THE SUBJECT'S GAZE POINT ON THE SCREEN** AND OBTAINS THE BUTTON
- **THEN, THE SYSTEM CONFIRMS OR CANCELS THE BUTTON ACCORDING TO EEG CLASSIFICATION**
- CLASSIFICATION RESULTS CAN BE TRAINED TO REACH A HIGH CLASSIFICATION ACCURACY (> 90%)

Images from Han, S., Liu, R., Zhu, C., Soo, Y. G., Yu, H., Liu, T., & Duan, F. (2016, December). Development of a human computer interaction system based on multi-modal gaze tracking methods. In *2016 IEEE International Conference on Robotics and Biomimetics (ROBIO)* (pp. 1894-1899). IEEE.

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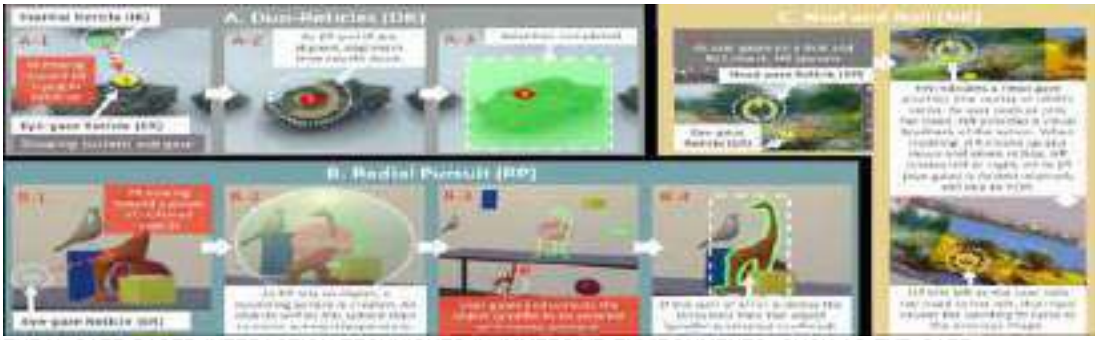
MIDAS TOUCH PROBLEM



NATURAL GAZE-BASED INTERACTION TECHNIQUES IN IMMERSIVE ENVIRONMENTS, SUCH AS EYE-GAZE SELECTION BASED ON **EYE GAZE AND INERTIAL RETICLES**, CLUTTERED OBJECT SELECTION THAT TAKES ADVANTAGE OF **SMOOTH PURSUIT**, AND **HEAD-GESTURE-BASED INTERACTION** RELYING ON THE **VESTIBULO-OCULAR REFLEX**

Images from Piumsomboon, T., Lee, G., Lindeman, R. W., & Billinghurst, M. (2017, March). Exploring natural eye-gaze-based interaction for immersive virtual reality. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)* (pp. 36-39). IEEE.

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GAZE TRACKING

REAL-TIME CALIBRATION, LOW POWER TRACKING

A STATISTICAL APPROACH TO CONTINUOUS SELF CALIBRATING EYE GAZE TRACKING FOR VR

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Cameras sees eyes in mirror and IR reflecting mirror

LED illuminator display

- AUTOMATIC **EYE GAZE TRACKING** CONTINUOUSLY **UPDATING EYE TO SCREEN MAPPING** IN REAL-TIME
- **THE ALGORITHM FINDS CORRESPONDENCES BETWEEN CORNEAL AND SCREEN SPACE MOTION GENERATING GPRS**
- A COMBINATION OF THOSE MODELS PROVIDES A CONTINUOUS **MAPPING FROM CORNEAL POSITION TO SCREEN SPACE POSITION.**

Images from Tripathi, S., & Guenter, B. (2017, March). A statistical approach to continuous self-calibrating eye gaze tracking for head-mounted virtual reality systems. In *2017 IEEE winter conference on applications of computer vision (WACV)* (pp. 862-870). IEEE.

A STATISTICAL APPROACH TO CONTINUOUS SELF CALIBRATING EYE GAZE TRACKING FOR VR

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IR illuminator creating glints

- AN IR ILLUMINATOR SHINES ON THE EYE, **CREATING BRIGHT GLINTS** ON THE SURFACE OF THE CORNEA
- TRACKLET MATCHING ALGORITHM TAKES INPUTS OF SYNCHRONIZED TIME SERIES OF **CORNEAL LOCATIONS** AND THE **COORDINATES OF ALL OBJECTS ON THE SCREEN SPACE** AND OUTPUTS **THE SINGLE OBJECT WHOSE TRAJECTORY IS MOST SIMILAR TO THAT OF THE EYE**

Images from Tripathi, S., & Guenter, B. (2017, March). A statistical approach to continuous self-calibrating eye gaze tracking for head-mounted virtual reality systems. In *2017 IEEE winter conference on applications of computer vision (WACV)* (pp. 862-870). IEEE.

UTLRA LOW POWER GAZE TRACKING FOR VIRTUAL REALITY

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- **LIGAZE USES AN ADDITIONAL SET OF PHOTODIODES FACING THE DISPLAY TO SENSE INCOMING SCREEN LIGHT**
- LIGAZE ESTIMATES THE REFLECTED SCREEN LIGHT FROM PUPIL
- 3D GAZE VECTORS ARE INFERRED IN REAL TIME USING SUPERVISED LEARNING (TREE REGRESSION ALGORITHM)
- **LIGAZE DETECTS THE BLINK EVENT** BY EXAMINING PHOTODIODE DATA OVER TIME

8 photodiodes per lens, light intensity at each photodiode

Images from Li, T., Liu, Q., & Zhou, X. (2017, November). Ultra-low power gaze tracking for virtual reality. In *Proceedings of the 15th ACM Conference on Embedded Network Sensor Systems* (pp. 1-14)., ***Sensys 2017***

FACEVR: REAL-TIME FACIAL REENACTMENT AND EYE GAZE CONTROL IN VIRTUAL REALITY

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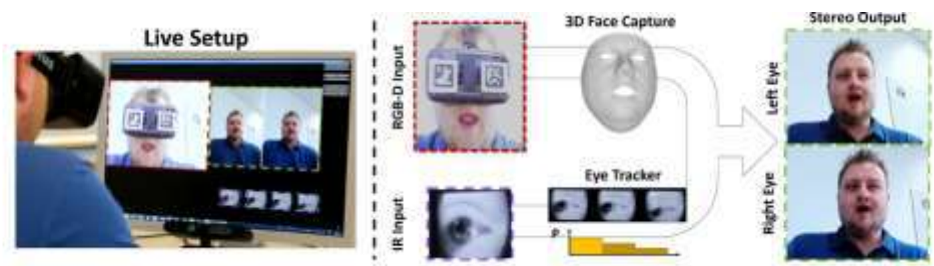

RGB-D camera, IR camera for eye gaze of one eye, 3D reconstructing face ‘Removing’ HMD

AR markers

- **FaceVR, a new real-time facial reenactment approach**
- In order to capture a face, **a commodity RGB-D sensor** with a frontal view; the eye region is tracked using a new data-driven approach based on data from **IR camera** located in the HMD
- AR markers in front of HMD to track the rigid pose of head
- Allowing artificial modifications of face and eye

Images from Thies, J., Zollhöfer, M., Stamminger, M., Theobalt, C., & Nießner, M. (2016). Facevr: Real-time facial reenactment and eye gaze control in virtual reality. *arXiv preprint arXiv:1610.03151*.

FRONT CAMERA EYE TRACKING FOR MOBILE VR

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Without infrared emitters, only from images of the selfie camera

- An innovative mobile VR eye tracking methodology, utilizing only the captured images of the front-facing (selfie) camera The
- The system enhances the low-quality camera-captured images that suffer from low contrast and poor lighting by applying a pipeline of customized low level image enhancements to suppress obtrusive reflections due to the headset lenses.
- A formal study confirms that the presented eye tracking methodology performs comparably to eye trackers in commercial VR headsets when the eyes move in the central part of the headset's field of view

Image from Drakopoulos, P., Koulieris, G. A., & Mania, K. (2021). Eye Tracking Interaction on Unmodified Mobile VR Headsets Using the Selfie Camera. *ACM Transactions on Applied Perception (TAP)*, *18*(3), 1-20. IEEE.

RESEARCH CHALLENGES

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- **Eye tracking and Augmented reality** glasses introducing additional constraints in terms of power consumption and physical size of the tracking hardware. More research needed on mobile, small-scale, low-power, robust and accurate eye-tracking technology for AR under arbitrary lighting conditions and longer periods of time.
- **Games and VR** experiences will greatly benefit from gaze information to enable enhanced user interfaces, more social interaction through eye contact and reduced computation efforts in rendering.
- **Eye tracking for commodity devices** requires security and privacy of the to prevent identity theft. Technologically, user customisation and automated device calibration, user profiling and user-friendly identification will be enabled when biometric eye data can be acquired on the fly.
- **Dealing with large quantities of eye trakcing data:** As eyetracking technologies become cheaper and more easily available (for example, webcam based eyetracking) it will become possible to obtain eye tracking information even by crowdsourcing viewers.

Koulieris, G. A., Akşit, K., Stengel, M., Mantiuk, R. K., Mania, K., & Richardt, C. (2019, May). Near-eye display and tracking technologies for virtual and augmented reality. In *Computer Graphics Forum* (Vol. 38, No. 2, pp. 493-519).

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PROF. KATERINA MANIA

TECHNICAL UNIVERSITY OF CRETE, GREECE

Research team **SURREAL**

http://surreal.tuc.gr

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GAZE-AWARE DISPLAYS AND INTERACTION

FOVEATED RENDERING

RENDERING

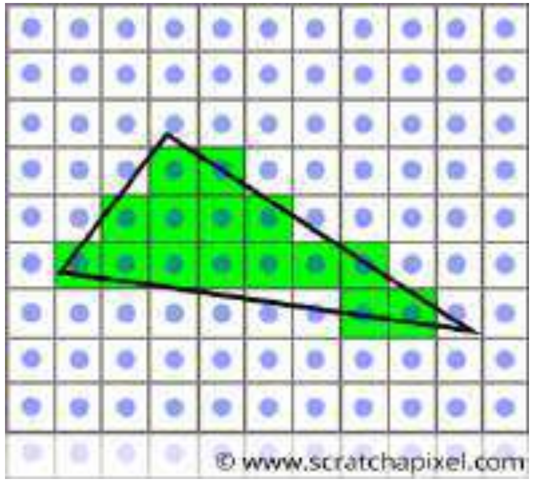
RESTRICTIONS

- Display Hardware
  - Increase pixel density (FHD→ UHD)
  - Higher refresh rate
  - Higher field of view
- Various algorithms performance and Quality in software rendering for virtual reality
  - Rasterization (High-performance, low Quality)
  - Ray tracing (low-performance, High Quality)
  - Path tracing (lowest-performance, Ultra Quality)
  - Instant Radiosity (lowest-performance, High Quality)
- High frame rate is required for virtual reality

PROPOSED SOLUTION

- Human Visual System limited rendering
  - Reduce acuity in the periphery as eccentricity increase
- Foveated rendering, adjust rendering using visual Perception as the optimizing function
- Non-uniform rendering

RASTERIZATION



- Find the closest triangle seen by pixel, discard all other geometry
- Shading without having information from the 3D environment.
- Pros
  - Faster technique
  - Many techniques to increase performance and quality
    - Lighting probes to make pseudo-realistic light, LOD etc.
- Cons
  - Not photo-realistic compare to other rendering algorithms
  - Reflections, refractions, and shadows effects are not accurate.
  - Global illumination is costly to be implemented.
  - Not fast enough for VR in some case

Top and bottom left image: https://docs.unrealengine.com/4.26/en-US/RenderingAndGraphics/RayTracing/

Right Image: https://www.scratchapixel.com/index.php

FOVEATED RASTERIZATION

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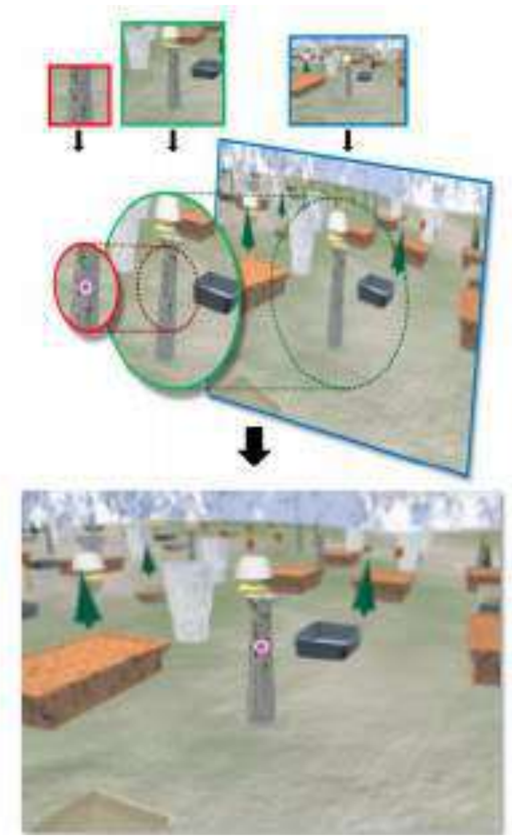
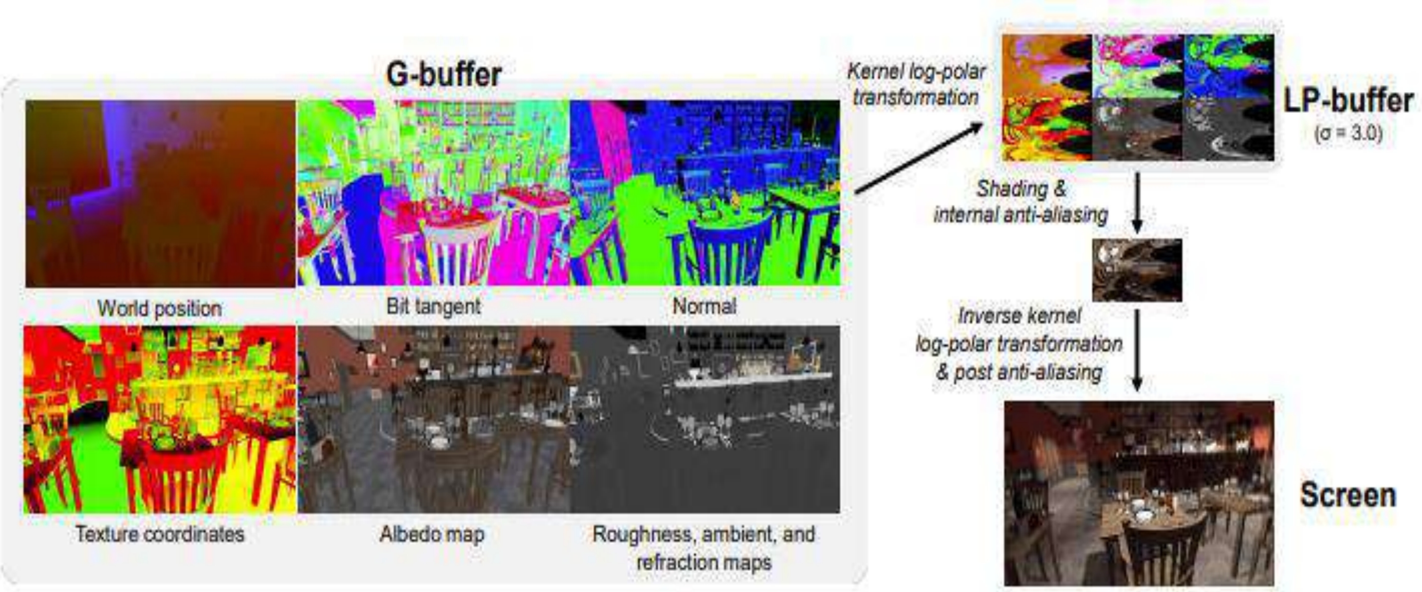


- Three Layers rendering
- Each layer has different resolution and LOD
- Layers are blended and smothened
- Updating half the temporal rate of the inner layer
- Post-processing to cover artifacts
  - Progressive Blur results to tunnel vision
  - Enhance contrast to eliminate tunnel vision
- Pros
  - Higher performance due to reduction in LOD
- Cons
  - Artifacts due to extreme reductions in LOD

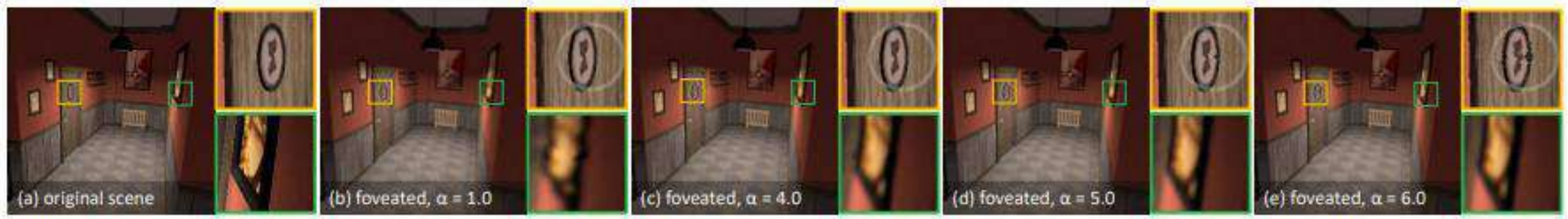
Left image: Guenter, Brian, et al. "Foveated 3D graphics." *ACM Transactions on Graphics (TOG)* 31.6 (2012): 1-10.

Top and bottom right images: Patney, Anjul, et al. "Towards foveated rendering for gaze-tracked virtual reality." *ACM Transactions on Graphics (TOG)* 35.6 (2016): 1-12.ka

FOVEATED RASTERIZATION

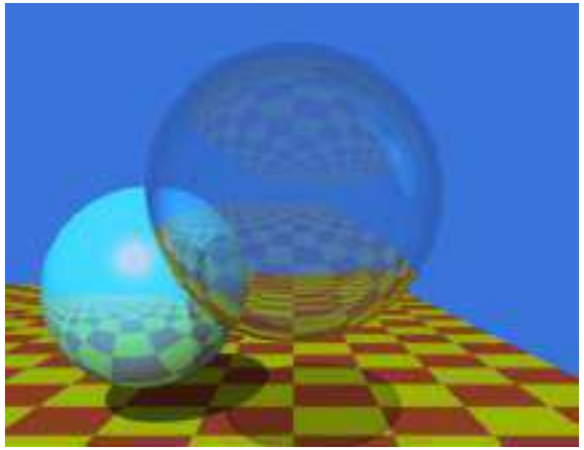


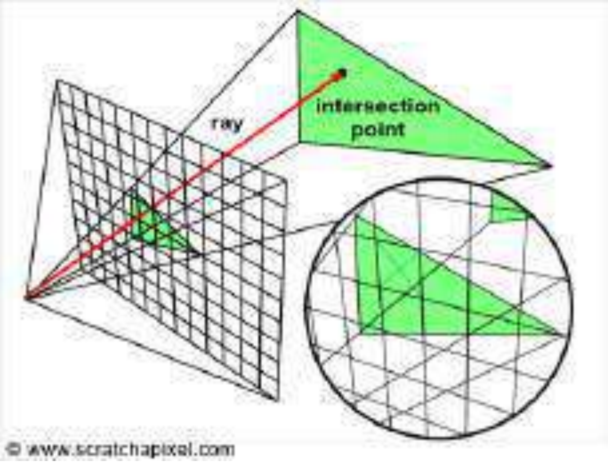
- Use Deferred Rendering to produce GBuffer
- Transform the GBuffer from Cartesian to Polar coordinates to a reduced resolution log-polar buffer (LP-Buffer)
- Apply shading and anti-aliasing using the LP-Buffer
- Inverse transform from polar to cartesian coordinates and map the result to full resolution



Images: Meng, Xiaoxu, et al. "Kernel foveated rendering." *Proceedings of the ACM on Computer Graphics and Interactive Techniques* 1.1 (2018): 1-20.

RAY TRACING





- Generate primary rays for each pixel and trace them
- Send ray through pixel and find the closest triangle to the pixel
- Rays change directions based on material properties
- Produce secondary rays based on material surface properties and the light sources
- Pros
  - Accurate reflections & refractions
  - Easy to implement global illumination
- Cons
  - Slow compare to Rasterization

Top Lef image: Parker, Steven G., et al. "Optix: a general purpose ray tracing engine." *Acm transactions on graphics (tog)* 29.4 (2010):

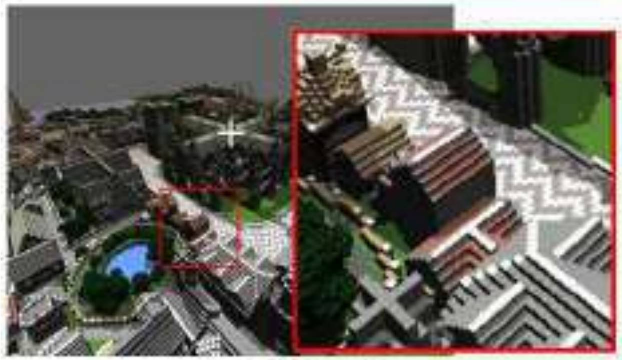
Top right image: https://www.scratchapixel.com/index.php?redirect

Bottom Images: https://docs.unrealengine.com/4.26/en-US/RenderingAndGraphics/RayTracing/

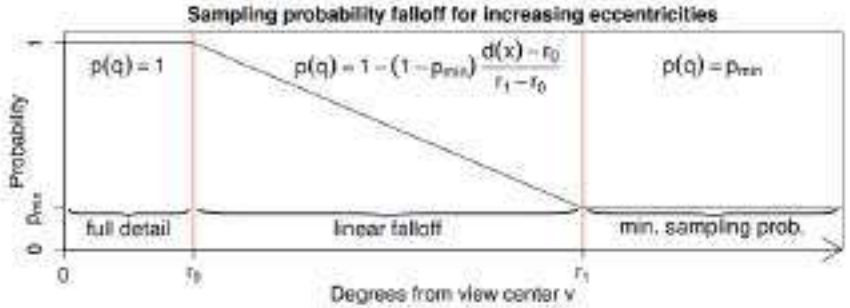
FOVEATED REAL-TIME RAY TRACING FOR HEAD-MOUNTED DISPLAYS

(a) Small foveal region with ($r_0 = 5°, r_1 = 10°, p_{min} = 0.01$)

(b) Medium foveal region with ($r_0 = 10°, r_1 = 20°, p_{min} = 0.05$)



(c) Full Renderer



- Some primary rays are not generated based on a linear probability model
- Use reprojected frames and a support image has a lower resolution to fill the empty pixels
- Post-processing to improve quality
  - Use of blur to cover artifacts
  - Use of Depth of field to improve quality
- Pros
  - Increase performance due to the reduction of generated rays
- Cons
  - Artifacts appear in small foveal regions
  - Flickering in the periphery

Images: Weier, Martin, et al. "Foveated real-time ray tracing for head-mounted displays." *Computer Graphics Forum*. Vol. 35. No. 7. 2016.

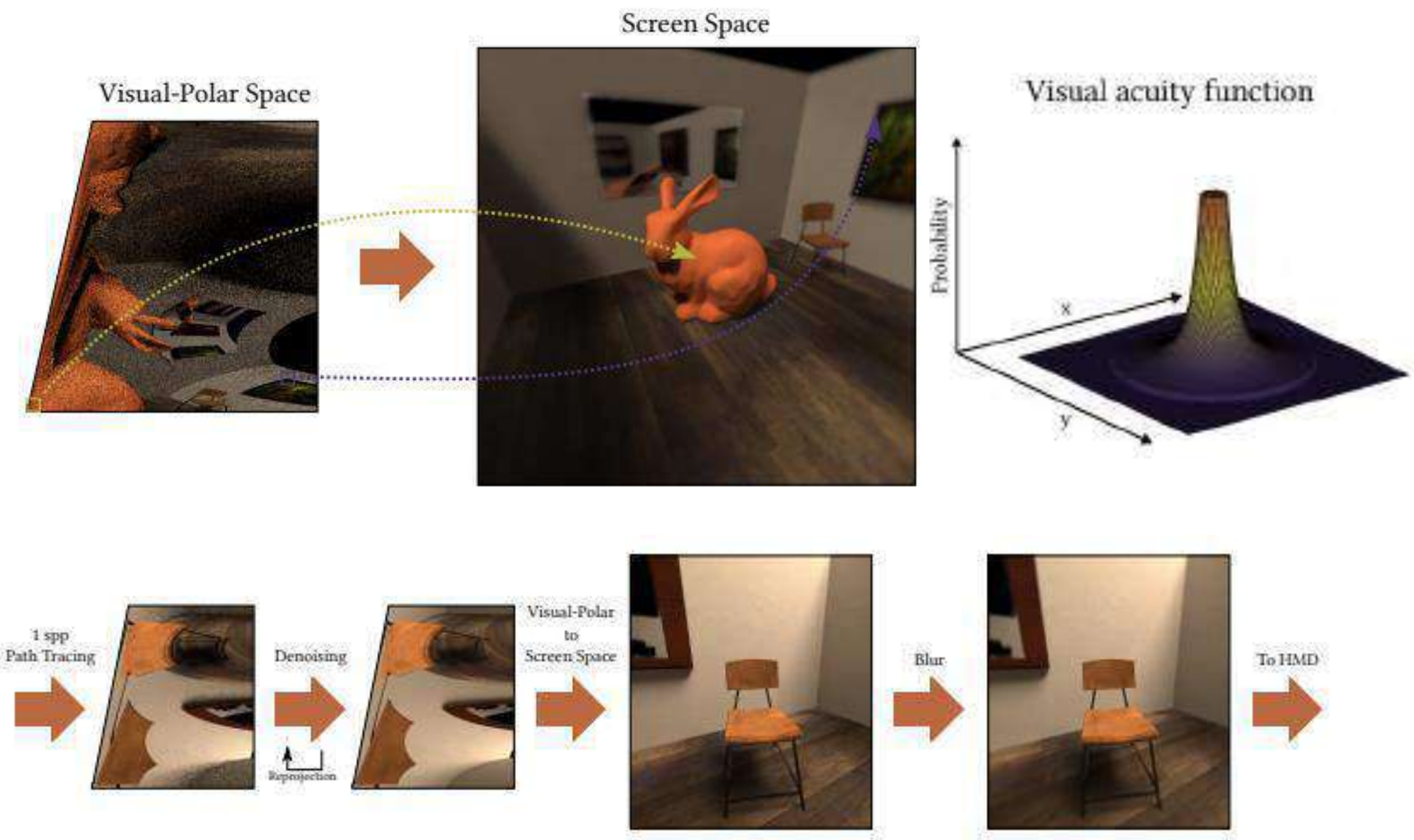
PATH-TRACING

- Path-tracing uses stochastic sampling during the intersection of a ray with a triangle based on material surface properties
- Use of Denoisers to reduce the samples per pixel to one sample
  - Not enough for virtual reality rendering
- Pros
  - Global illumination, simple implementation
  - Higher Accuracy to reflections, refractions, and soft shadows compare to ray tracing
- Cons
  - Requires many samples to produce images without noise (more rays per pixel)
  - Slow to converge
  - Extremely slow compared to rasterization and ray-tracing

Top image: Schied, Christoph, et al. "Spatiotemporal variance-guided filtering: real-time reconstruction for path-traced global illumination." *Proceedings of High Performance Graphics*. 2017. 1-12.

Bottom left and right images: https://docs.unrealengine.com/4.26/en-US/RenderingAndGraphics/RayTracing/PathTracer/

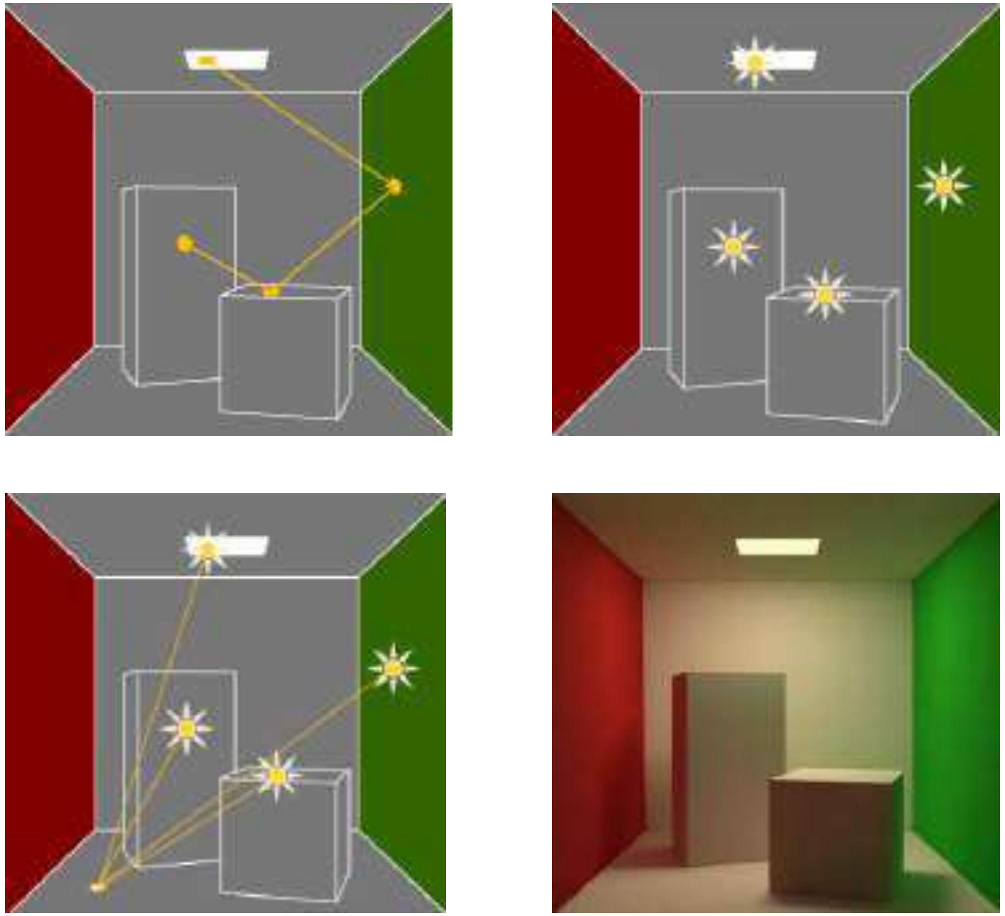
FOVEATED RENDERING IN PATH-TRACING



- Use of a visual-polar model which matches the human visual acuity
- Denoising and path tracing render in polar coordinates at a lower resolution and are then mapped to the target resolution in screen space
- Pros
  - Primary rays stay more coherent (better utilization of hardware)
  - Improve denoising quality in the fovea
  - 2.5x speedup for path-tracing
- Cons
  - Not a dedicated temporal anti-aliasing method
    - Could reduce the artifacts in the periphery

Images: Koskela, Matias, et al. "Foveated real-time path tracing in visual-polar space." *Proceedings of 30th Eurographics Symposium on Rendering*. The Eurographics Association, 2019.

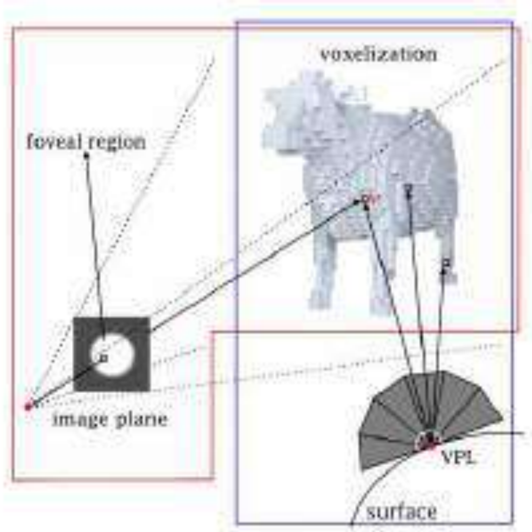
INSTANT RADIOSITY (IR)

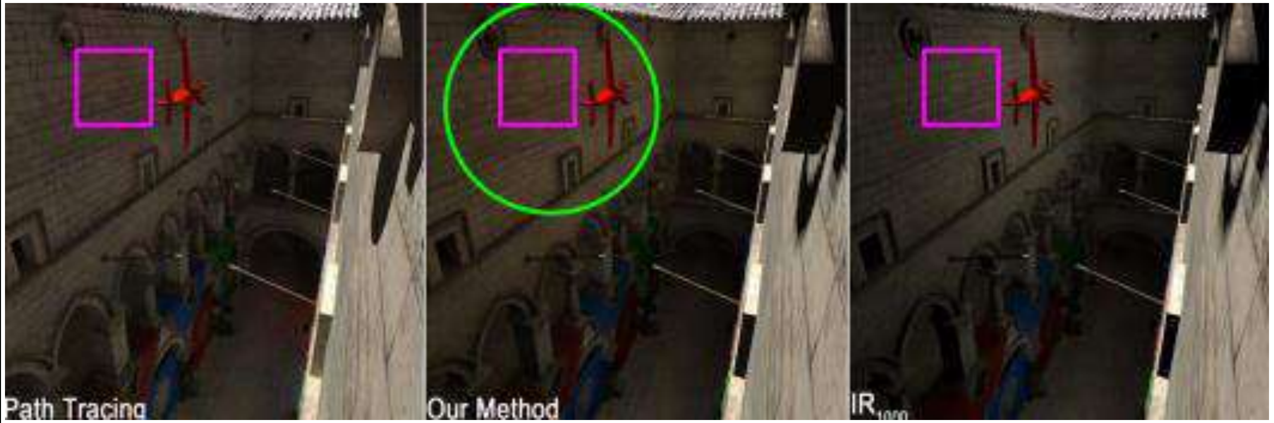


- Light is traced from the light source to the 3D environment
- The intersection points during the trace are considered Virtual Point Lights (VPLs)
- The scene is rendered several times for each light source.
- Pros
  - No noise compare to path-tracing
- Cons
  - Create Artifacts
  - Calculates only diffused surfaces

Images: http://www.cs.cornell.edu/courses/cs6630/2012sp/slides/Boyadzhiev-Matzen-InstantRadiosity.pdf

FOVEATED IN INSTANT RADIOSITY

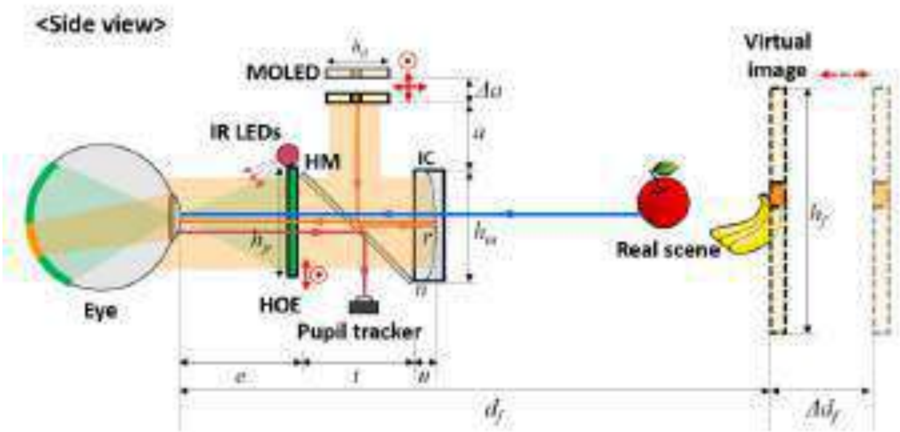


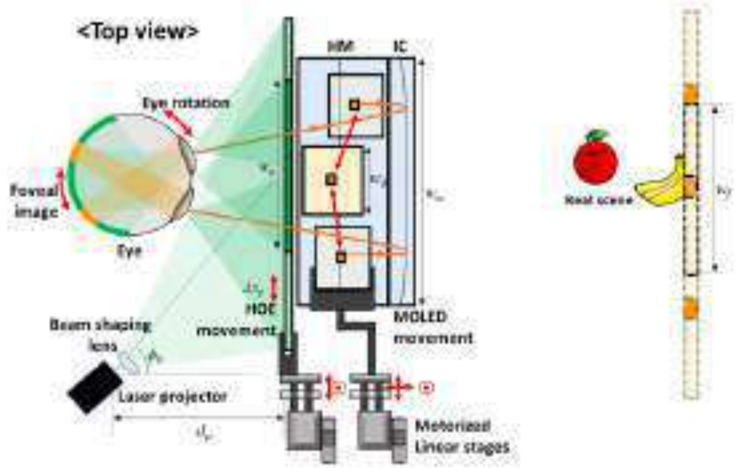


- Create a voxelization of the Scene
- Voxel foveated weight estimation.
  - Each visible voxel in the scene voxelization from the current viewpoint is projected on the image plane to obtain the foveated weight
- Trace rays from viewpoint based on image plane instead from light sources
  - One bounce for each sample point to generate Virtual Point Light (VPL) candidate
  - Uniform sampling for VPL generation in the foveal region
  - Define foveated importance for each VPL using the define weights
- Propose a VPL reuse scheme, updates only a small fraction of VPLs
- Pros
  - ensures temporal coherence and improves time efficiency
  - dynamic scenes, high quality in the foveal, high frame rates
  - accurate global illumination effects in the foveal region
- Cons
  - Doesn't work well with rapidly moving objects
  - Less accurate global illumination in the peripheral region
  - Flickering due to rapidly moving objects

Top left and bottom Images: Wang, Lili, et al. "Foveated Instant Radiosity." *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, 2020.

FOVEATED AR



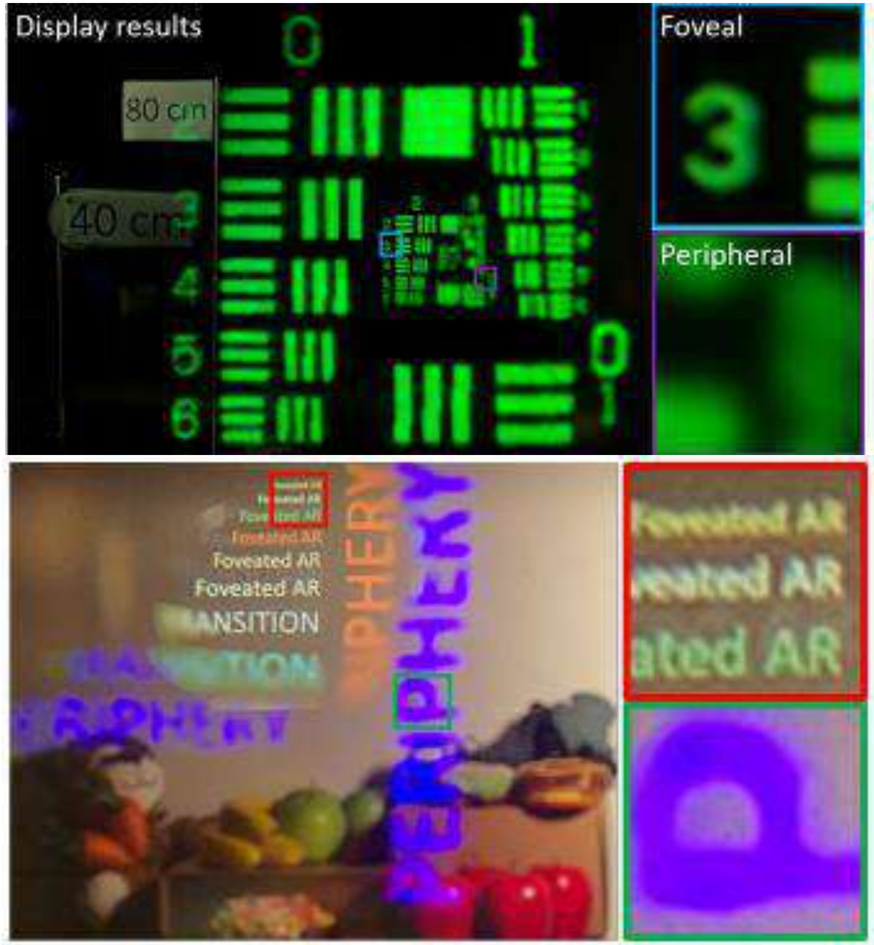


Wearable Display Prototype

- Develop a prototype AR display by adopting foveated at hardware
- Two displays
  - High-resolution, small FOV, foveal display: micro OLED (MOLED)
  - Low-resolution, large FOV, peripheral display: Maxwellian-view
- The light path of fovea, eye tracking and real scene are combined in a half mirror (HM) and image combiner (IC)
- The peripheral display is moved based on user gaze direction along the horizontal axis to move the high resolution display to match the user's eye movements
- The MOLED can move vertically to dynamically change the virtual depth

Images: Kim, Jonghyun, et al. "Foveated AR: dynamically-foveated augmented reality display." *ACM Transactions on Graphics (TOG)* 38.4 (2019): 1-15.

FOVEATED AR



- Color intensity matching by applying gamma correction between the two displays
- Linear Gaussian blur used to blend the two images
- Depth adjustment for varifocal visuals
- Pros
  - simultaneous wide FOV (100◦ diagonal), compact form factor, high foveal resolution (60 cpd), variable focus display and rendering, and large eyebox (12 mm × 8 mm)
  - use of a holographic element with dynamic position driven by gaze tracking
- Cons
  - Mechanical complexity, not for commercial use yet
  - The projector might collide with the wearer’s eyelashes due to small eye relief

CONCLUSIONS & CHALLENGES

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- **Conclusions**
  - Heavily computational algorithms become affordable with foveated rendering without any perceived drop in quality
  - Foveated Rendering idea can be use to optimize hardware to increase the specifications of current near-eye displays
  - Increasing rendering performance and hardware capabilities fundamental for widespread adoption of near-eyes displays
- **Researches Challenges**
  - Aliasing in the periphery
  - Flickering in dynamic scenes
  - Eye tracking accuracy
  - Hardware restrictions (AR mostly)

POLYCHRONAKIS ANDREAS

PH.D. CANDIDATE

Technical University of Crete

- I am a researcher and Ph.D. candidate at the School of Electrical and Computer Engineering, Technical University of Crete, Greece. My area of expertise is focused on foveated rendering pipelines for computer Graphics.
- This research forms part of the project 3D4DEPLHI which is co-financed by the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call 'Specific Actions, Open Innovation for Culture' (project code: T6YBΠ-00190)

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VIRTUAL ENVIRONMENTS AND EYE TRACKING

ANN MCNAMARA

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EYE MOVEMENTS

THE HUMAN EYE

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2

2

THE HUMAN EYE

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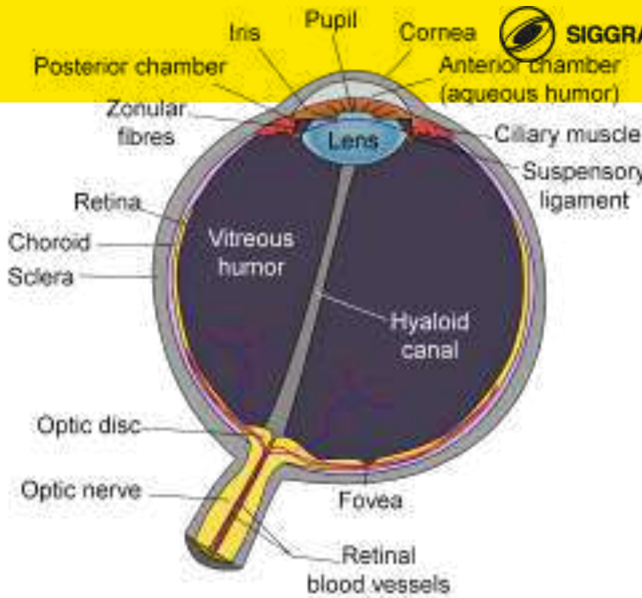

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THE HUMAN EYE

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F: Foveal area (1-2°). Pf: Para-foveal area (2-5°). P: Peripheral area (6-220°).

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A BRIEF HISTORY OF EYE TRACKING

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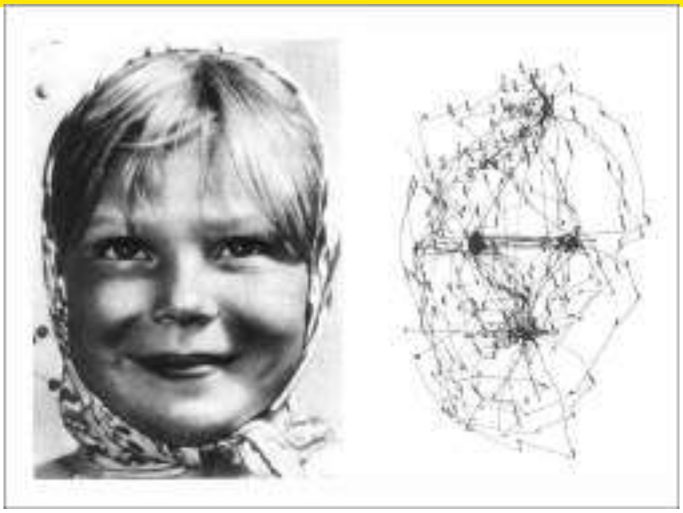

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TYPES OF EYE MOVEMENTS

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6

SACCADES

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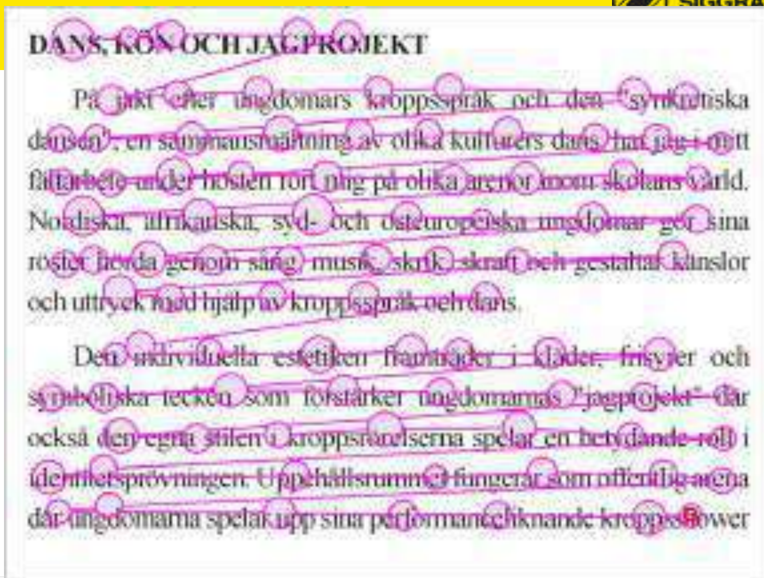
Rapid Eye Movements to quickly reposition the eye



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FIXATIONS

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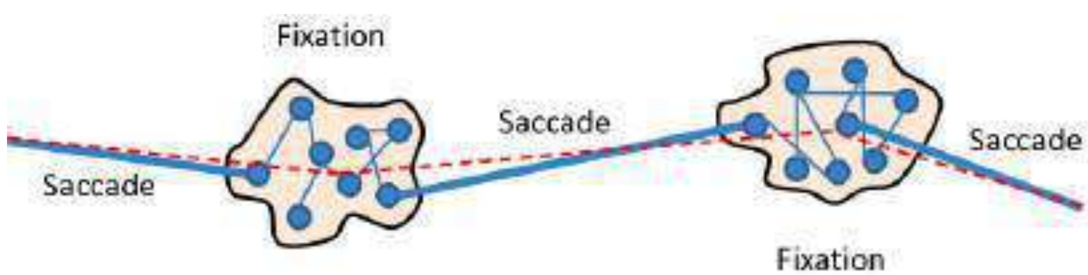

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SMOOTH PURSUIT

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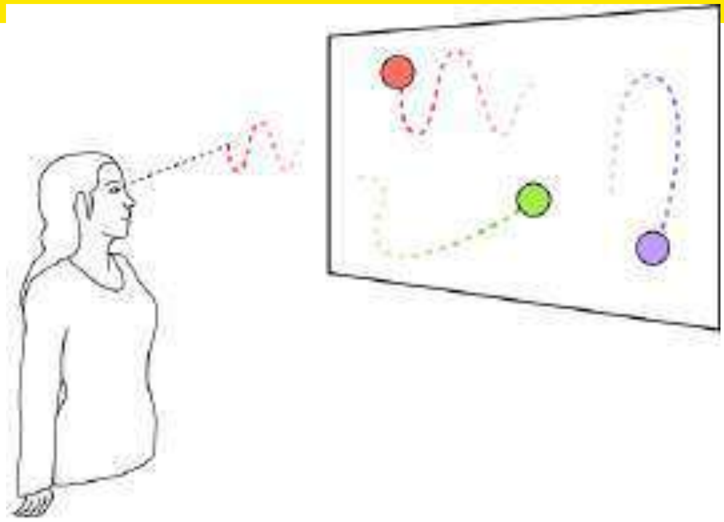

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OTHER MEASURES

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- Blink Frequency
- Pupil Dilation

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VIRTUAL ENVIRONMENTS AND EYE TRACKING

EYE TRACKING IN VR

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IMMERSIVE VIRTUAL ENVIRONMENTS

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HOW IMMERSIVE EYE TRACKERS WORK

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AVAILABLE HARDWARE

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AVAILABLE HARDWARE

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AVAILABLE HARDWARE

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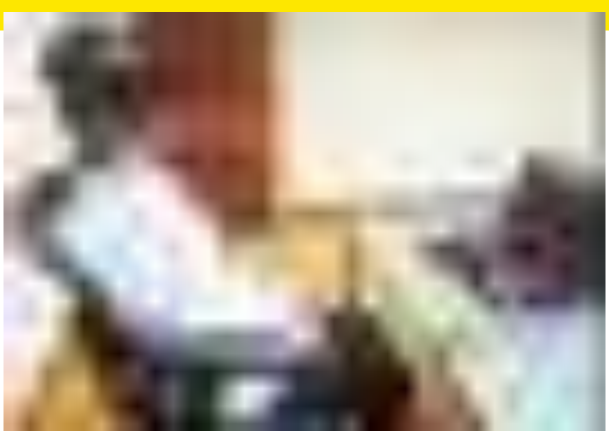

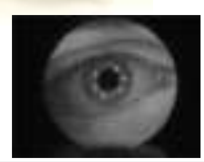

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Device	Eye Image Resolution	Sample Rate (Hz)	Cost (USD)
7invensun	-	120	$200
FOVE VR HMD	320 x 240	120	$599
aGlass and aSee	-	120-380	-
Pupil Labs VR (VIVE USB)	320 x 240	30	$1,572*
Pupil Labs VR (Dedicated USB)	640 x 480	120	$1,572*
Pupil Labs AR (Hololens)	640 x 480	120	$1,965*
Pupil Pro Glasses	800 x 600	200	$2,066?*
Pupil Pro Glasses	800 x 600	200	$2,066?*
Looxid Labs	-	-	$2999
Hololens v2	-	-	$3500
Tobii Pro Glasses 2	240 x 960	100	$10,000

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SPECIAL CONSIDERATIONS FOR EYE TRACKING IN VR

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VR RELEVANT PARAMETERS

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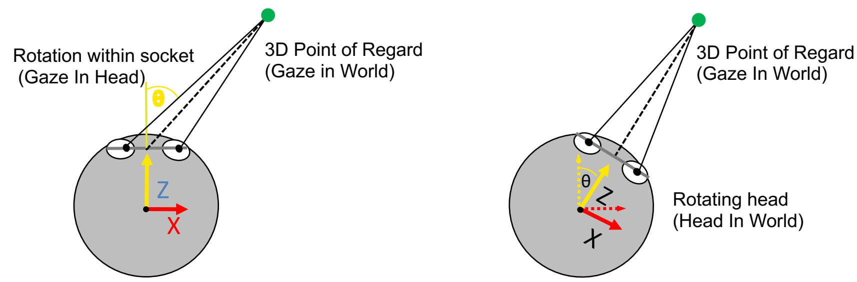

(Eyes rotated within the head's coordinate frame)

(Head rotated within the global coordinate frame)

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VERGENCE

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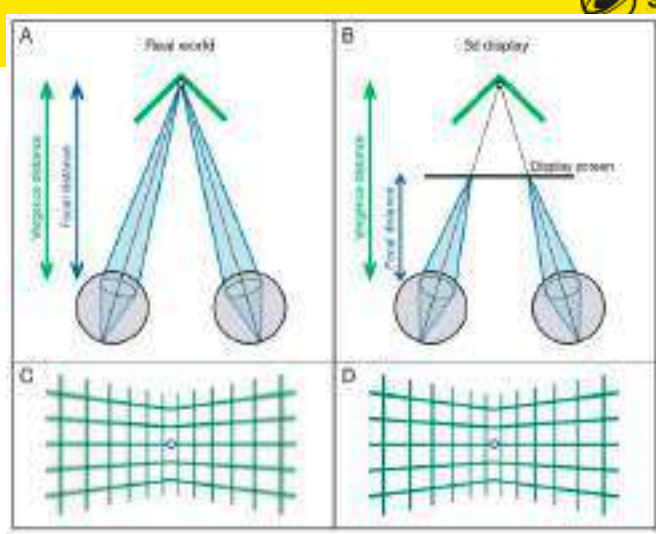

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VERGENCE AND ACCOMMODATION

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COLLECTING DATA

AN OVERVIEW OF HARDWARE AVAILABLE

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CALIBRATION

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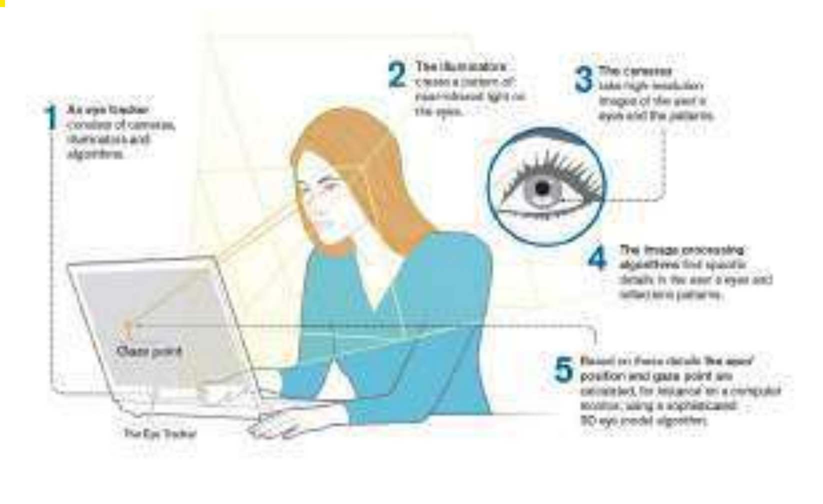

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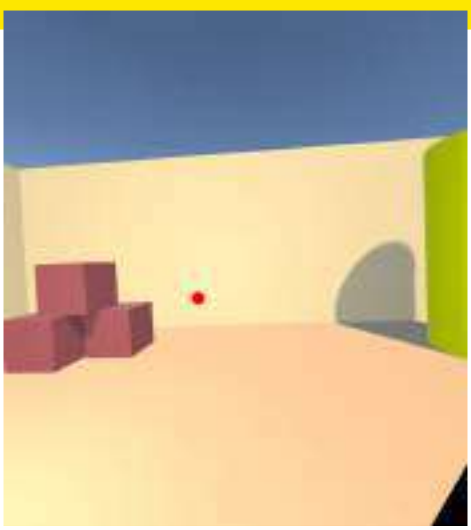
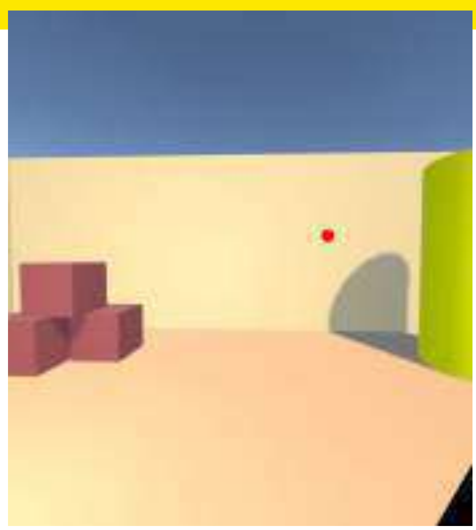
CALIBRATION

SIGGRAPH 2021





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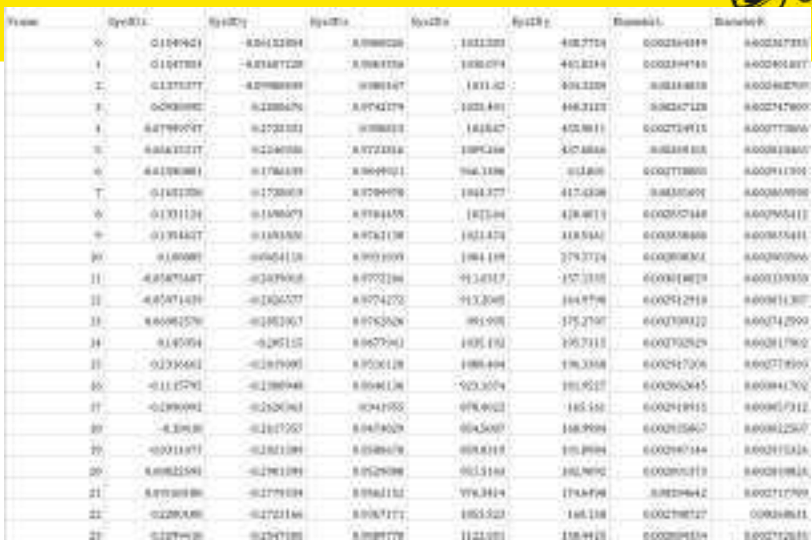
DATA



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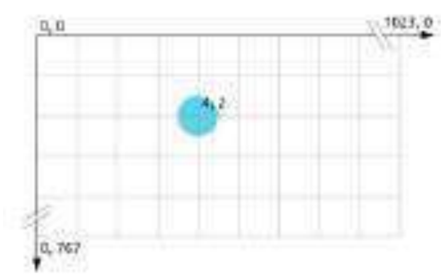
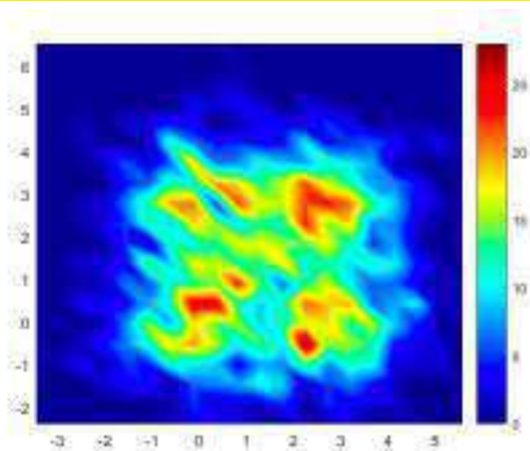
PARSING DATA





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DATA MEASURES

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GAZE PATTERNS

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HEATMAPS

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VR HEATMAP

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VR HEATMAP

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FIXATION ANALYSIS

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- Time to first Fixation
- Fixation Duration
- Number of Fixations

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AREAS OF INTEREST

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OTHERS

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- Number of times gaze returned
- Number of Respondents (as a %) that were drawn to an AOI

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TRENDS AND A LOOK TO THE FUTURE

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THANK YOU

ANN@VIZ.TAMU.EDU

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