DOM-E5161 - Introduction to Virtual Reality
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Aalto University

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LECTURE 2: DISPLAY DEVICES AND HUMAN VISION

Adapted from lectures by

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University of South Australia

https://www.slideshare.net/marknb00/comp-4010-lecture-2-presence-in-virtual-reality

https://www.slideshare.net/marknb00/comp-4010-lecture4-vr-technology-visual-and-haptic-displays

Overview

- Presence in VR
- Perception and VR
- Human Perception
- Sight
- Visual Displays

PRESENCE

Presence ..

"The subjective experience of being in one place or environment even when physically situated in another"

Witmer, B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence: Teleoperators and virtual environments*, *7*(3), 225-240.

Immersion vs. Presence

- *Immersion:* describes the extent to which technology is capable of delivering a vivid illusion of reality to the senses of a human participant.
- *Presence:* a state of consciousness, the (psychological) sense of being in the virtual environment.
- So Immersion, defined in technical terms, is capable of producing a sensation of Presence
- Goal of VR: Create a high degree of Presence
  - Make people believe they are really in Virtual Environment

Slater, M., & Wilbur, S. (1997). A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments. *Presence: Teleoperators and virtual environments*, *6*(6), 603-616.

How to Create Strong Presence?

- Use Multiple Dimensions of Presence
  - Create rich multi-sensory VR experiences
  - Include social actors/agents that interact with user
  - Have environment respond to user
- What Influences Presence
  - Vividness – ability to provide rich experience (Steuer 1992)
  - Using Virtual Body – users can see themselves (Slater 1993)
  - Internal factors – individual user differences (Sadowski 2002)
  - Interactivity – how much users can interact (Steuer 1992)
  - Sensory, Realism factors (Witmer 1998)

Example: UNC Pit Room

- Key Features
  - Training room and pit room
  - Physical walking
  - Fast, accurate, room scale tracking
  - Haptic feedback – feel edge of pit, walls
  - Strong visual and 3D audio cues
- Task
  - Carry object across pit
    - Walk across or walk around
  - Dropping virtual balls at targets in pit
- http://wwwx.cs.unc.edu/Research/eve/walk_exp/

Typical Subject Behaviour

- Note – from another pit experiment
- https://www.youtube.com/watch?v=VVAO0DkoD-8

1'40"

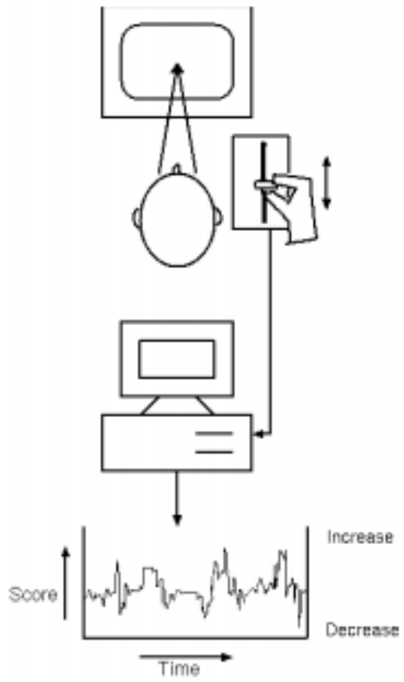
Benefits of High Presence

- Leads to greater engagement, excitement and satisfaction
  - Increased reaction to actions in VR
- People more likely to behave like in the real world
  - E.g. people scared of heights in real world will be scared in VR
- More natural communication (Social Presence)
  - Use same cues as face to face conversation

- Note: The relationship between Presence and Performance is unclear – still an active area of research

Measuring Presence

- Presence is very subjective so there is a lot of debate among researchers about how to measure it
- Subjective Measures
  - Self report questionnaire
    - University College London Questionnaire (Slater 1999)
    - Witmer and Singer Presence Questionnaire (Witmer 1998)
    - ITC Sense Of Presence Inventory (Lessiter 2000)
  - Continuous measure
    - Person moves slider bar in VE depending on Presence felt
- Objective Measures
  - Behavioural
    - reflex/flinch measure, startle response
  - Physiological measures
    - change in heart rate, skin conductance, skin temperature



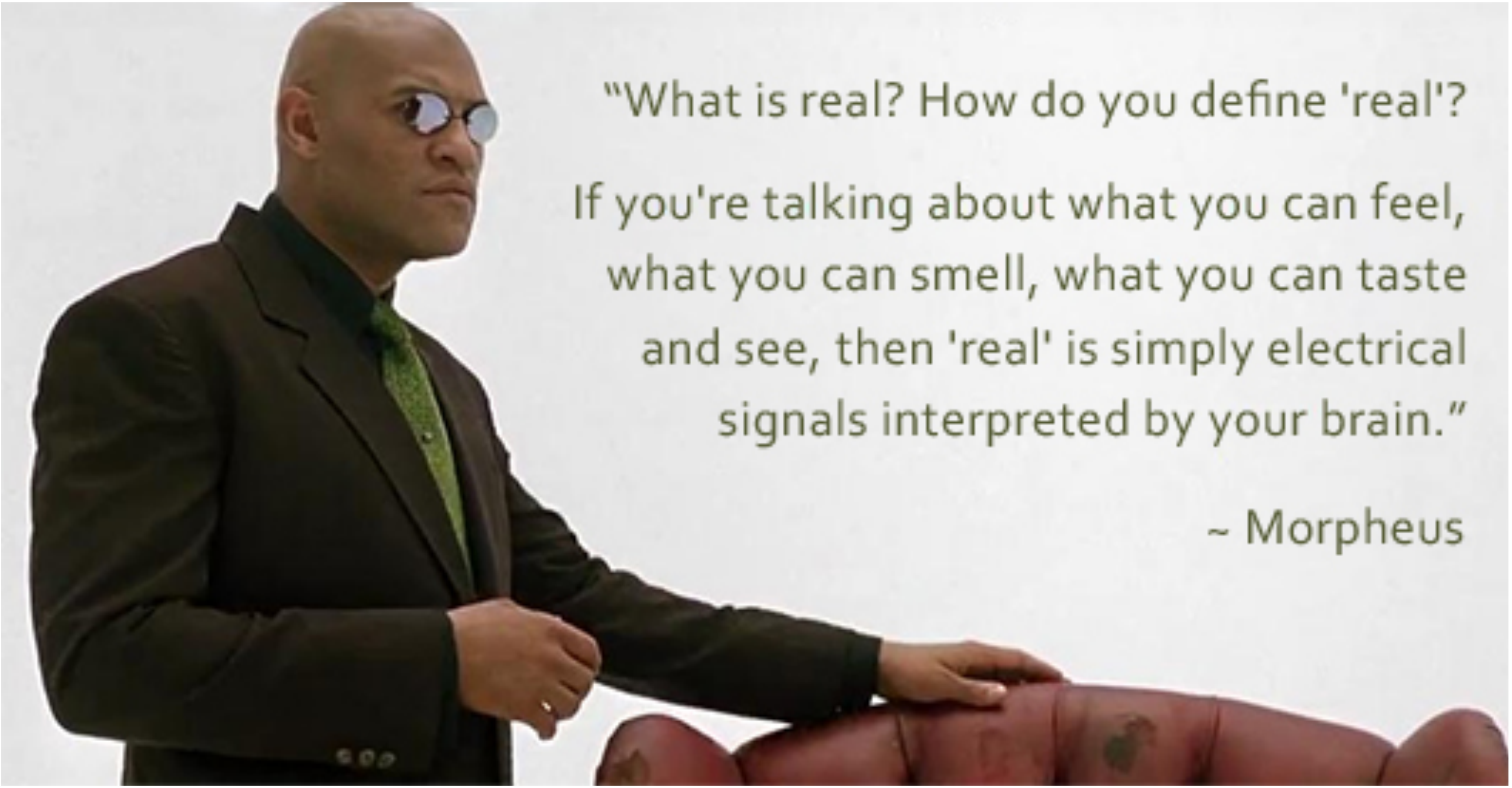
Presence Slider

Relevant Papers

- Slater, M., & Usoh, M. (1993). Representation systems, perceptual positions, and presence in immersive virtual environments. *Presence*, 2:221–233.
- Slater, M. (1999). Measuring presence: A response to the Witmer and Singer Presence Questionnaire. *Presence,* 8:560–565.
- Steuer, J. (1992). Defining virtual reality: Dimensions determining telepresence. *Journal of Communication*, 42(4):72–93.
- Sadowski, W. J. and Stanney, K. M. (2002) Measuring and Managing Presence in Virtual Environments. In: *Handbook of Virtual Environments: Design, implementation, and applications*.http://vehand.engr.ucf.edu/handbook/
- Schuemie, M. J., Van Der Straaten, P., Krijn, M., & Van Der Mast, C. A. (2001). Research on presence in virtual reality: A survey *CyberPsychology & Behavior*, *4*(2), 183-201.
- Lee, K. M. (2004). Presence, explicated. *Communication theory*, *14*(1), 27-50.
- Witmer, B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence: Teleoperators and virtual environments*, *7*(3), 225-240.
- Lessiter, J., Freeman, J., Keogh, E., & Davidoff, J. (2000). Development of a new cross-media presence questionnaire: The ITC-Sense of presence. Paper at the *Presence 2000 Workshop*, March 27–28, Delft.

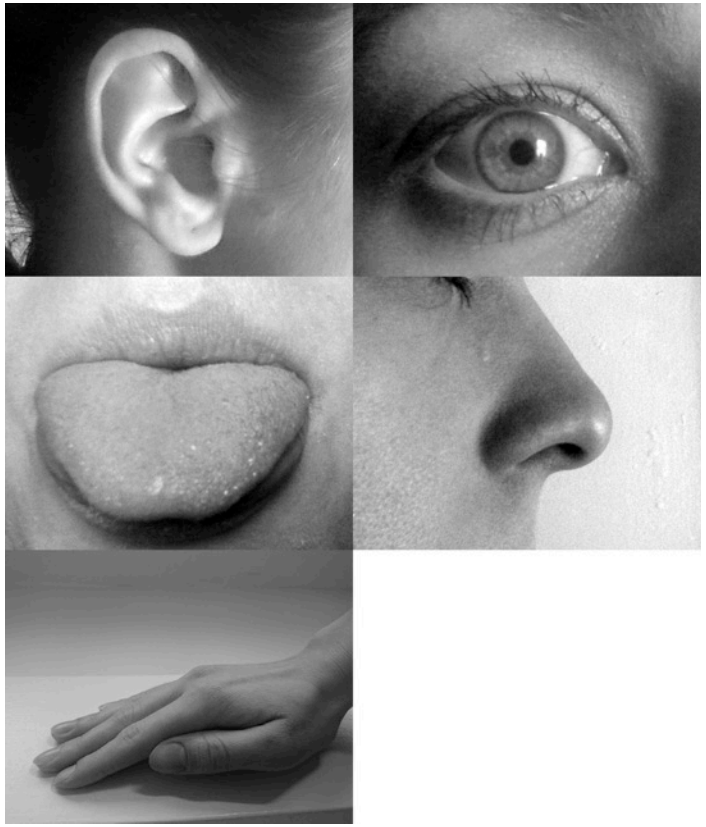
PERCEPTION AND VR

What is Reality?

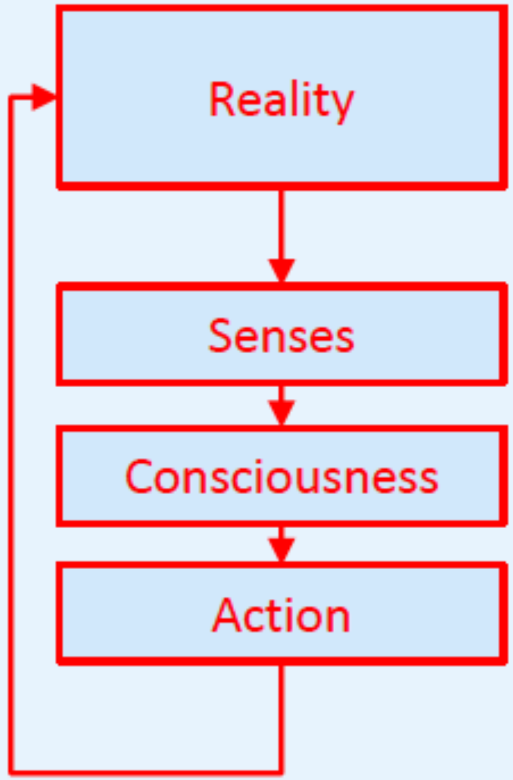


How do We Perceive Reality?

- We understand the world through our senses:
  - Sight, Hearing, Touch, Taste, Smell (and others..)
- Two basic processes:
  - Sensation – Gathering information
  - Perception – Interpreting information



Simple Sensing/Perception Model



Goal of Virtual Reality

".. to make it feel like you're actually in a place that you are not."

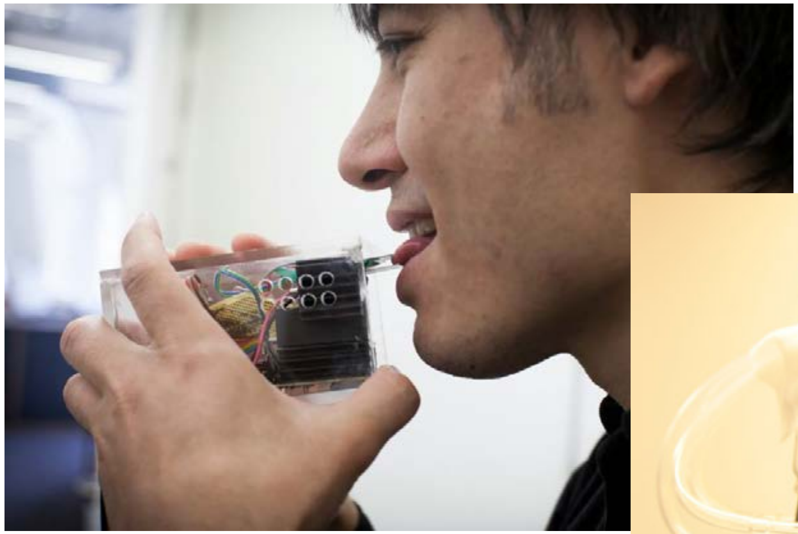
Palmer Luckey

Co-founder, Oculus

= presence

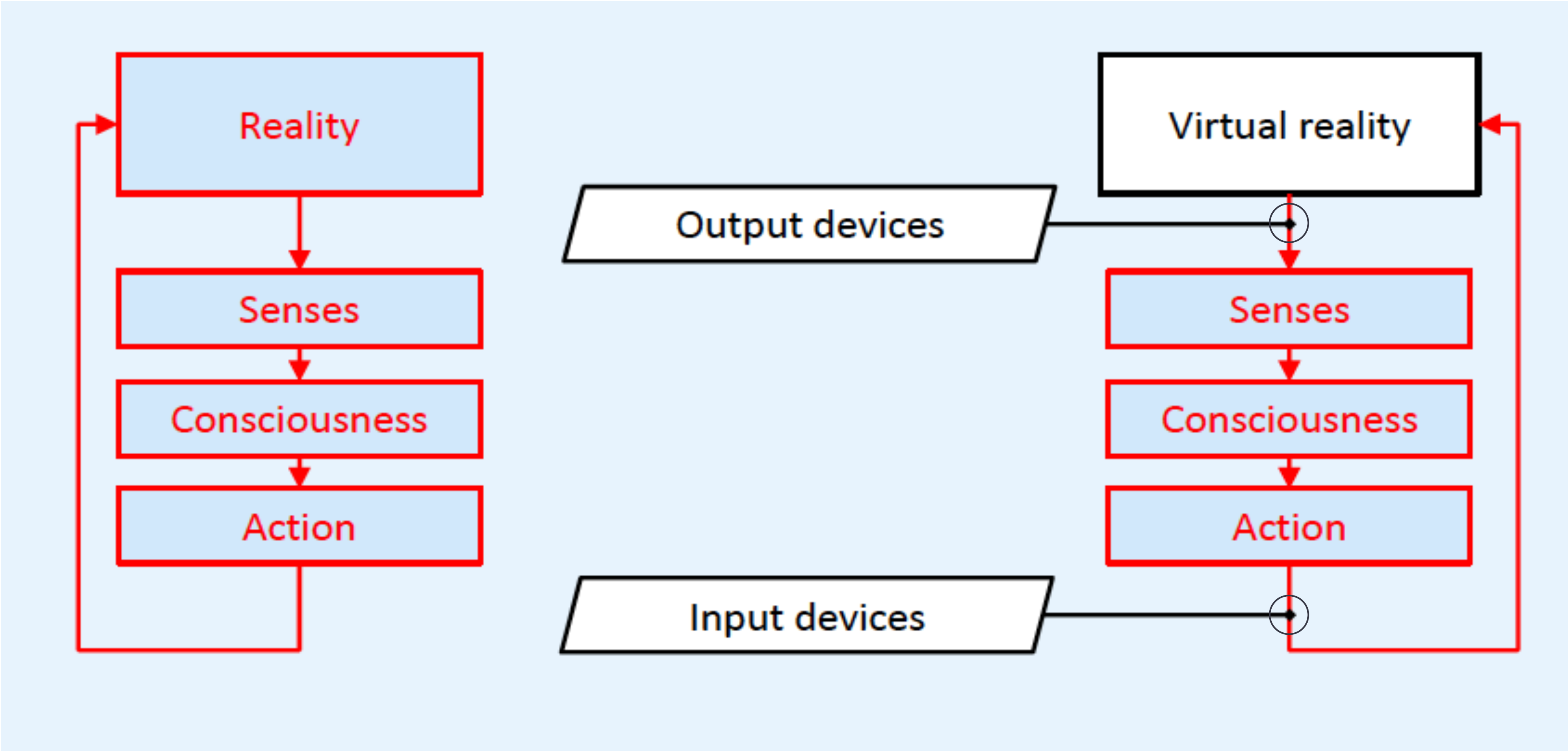
Creating the Illusion of Reality

- Fooling human perception by using technology to generate artificial sensations
  - Computer generated sights, sounds, smell, etc



= immersion

Reality vs. Virtual Reality



- In a VR system there are input and output devices between human perception and action

Example Birdly - http://www.somniacs.co/

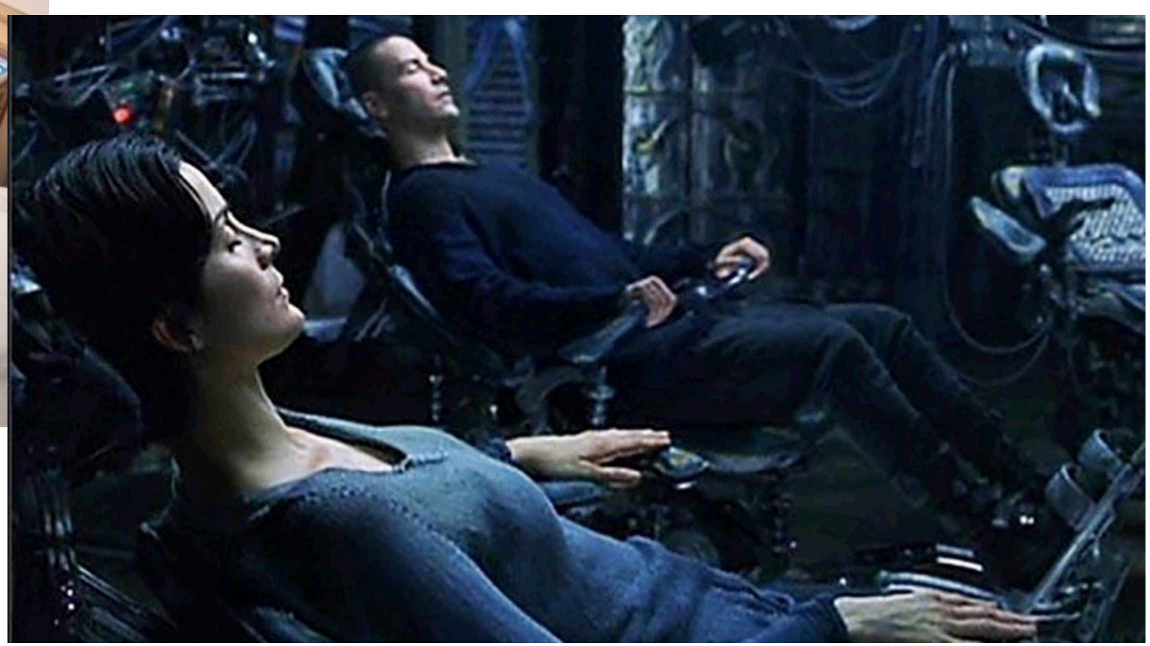
- Create illusion of flying like a bird
- Multisensory VR experience
  - Visual, audio, wind, haptic

Birdly Demo

1'02"

- https://www.youtube.com/watch?v=gHE6H62GHoM

Today



Tomorrow

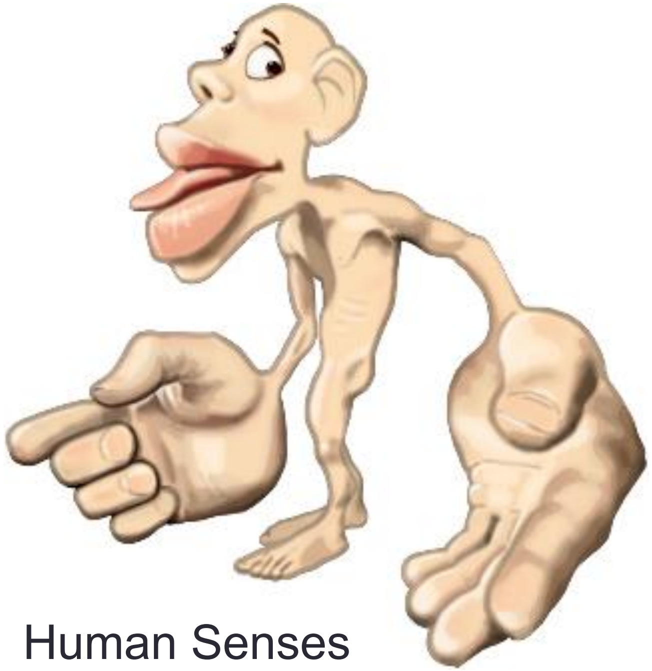
‘Virtual Reality is a synthetic sensory experience which may one day be indistinguishable from the real physical world.”

-Roy Kalawsky (1993)

HUMAN PERCEPTION

Motivation

VR Hardware



Human Senses

- Understand: In order to create a strong sense of Presence we need to understand the Human Perception system
- Stimulate: We need to be able to use technology to provide real world sensory inputs, and create the VR illusion

Senses

- How an organism obtains information for perception:
  - Sensation part of **Somatic Division** of **Peripheral Nervous System**
  - Integration and perception requires the **Central Nervous System**
- Five major senses:
  - Sight (Opthalamoception)
  - Hearing (Audioception)
  - Taste (Gustaoception)
  - Smell (Olfacaoception)
  - Touch (Tactioception)

Other Lesser Known Senses..

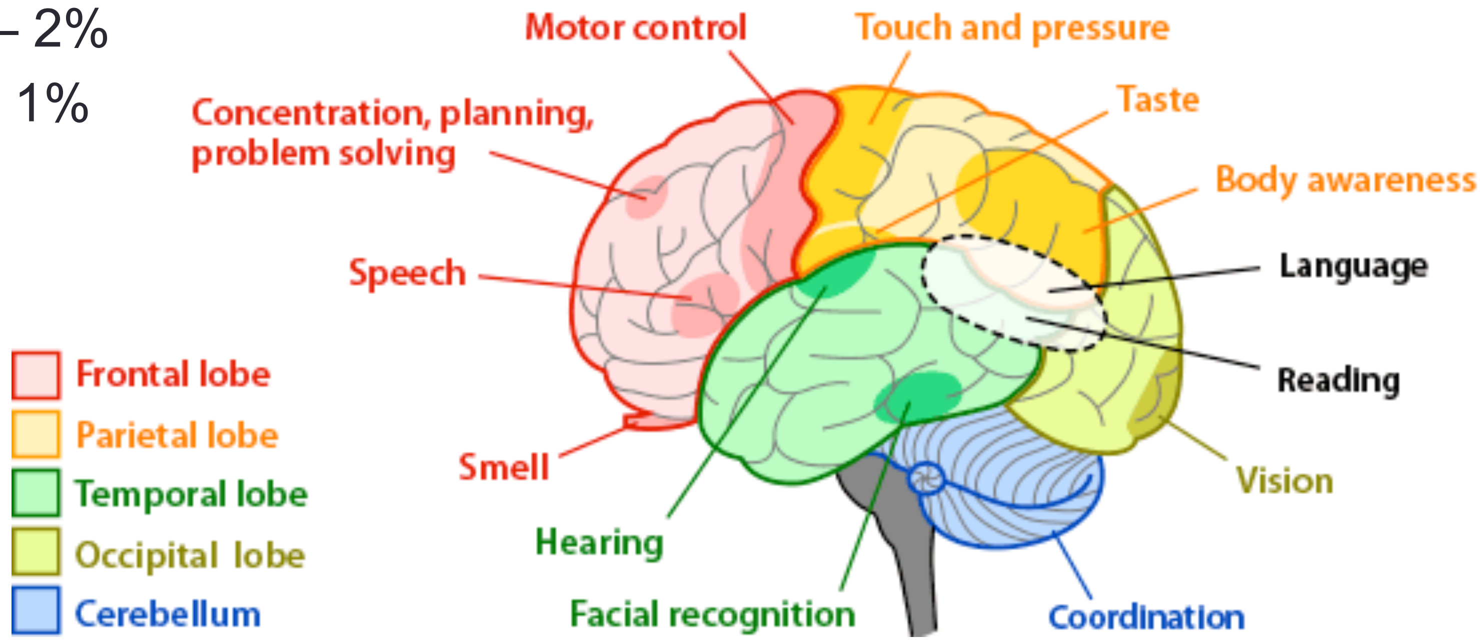
- Proprioception = sense of body position
  - what is your body doing right now
- Equilibrium = balance
- Acceleration
- Nociception = sense of pain
- Temperature
- Satiety (the quality or state of being fed or gratified to or beyond capacity)
- Thirst
- Micturition
- Amount of CO_2 and Na in blood

Relative Importance of Each Sense

- Percentage of neurons in brain devoted to each sense
  - Sight – 30%
  - Touch – 8%
  - Hearing – 2%
  - Smell - < 1%

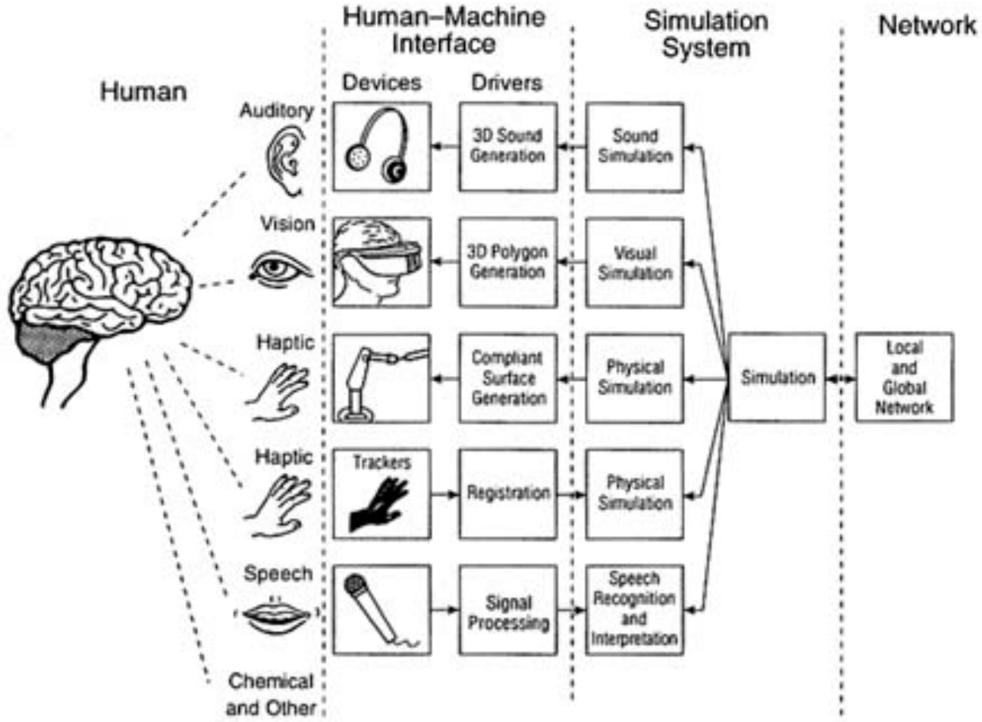
- Over 60% of brain involved with vision in some way

Primary brain areas:



VR System Overview

- Simulate output
- Map output to devices
- Use devices to stimulate the senses



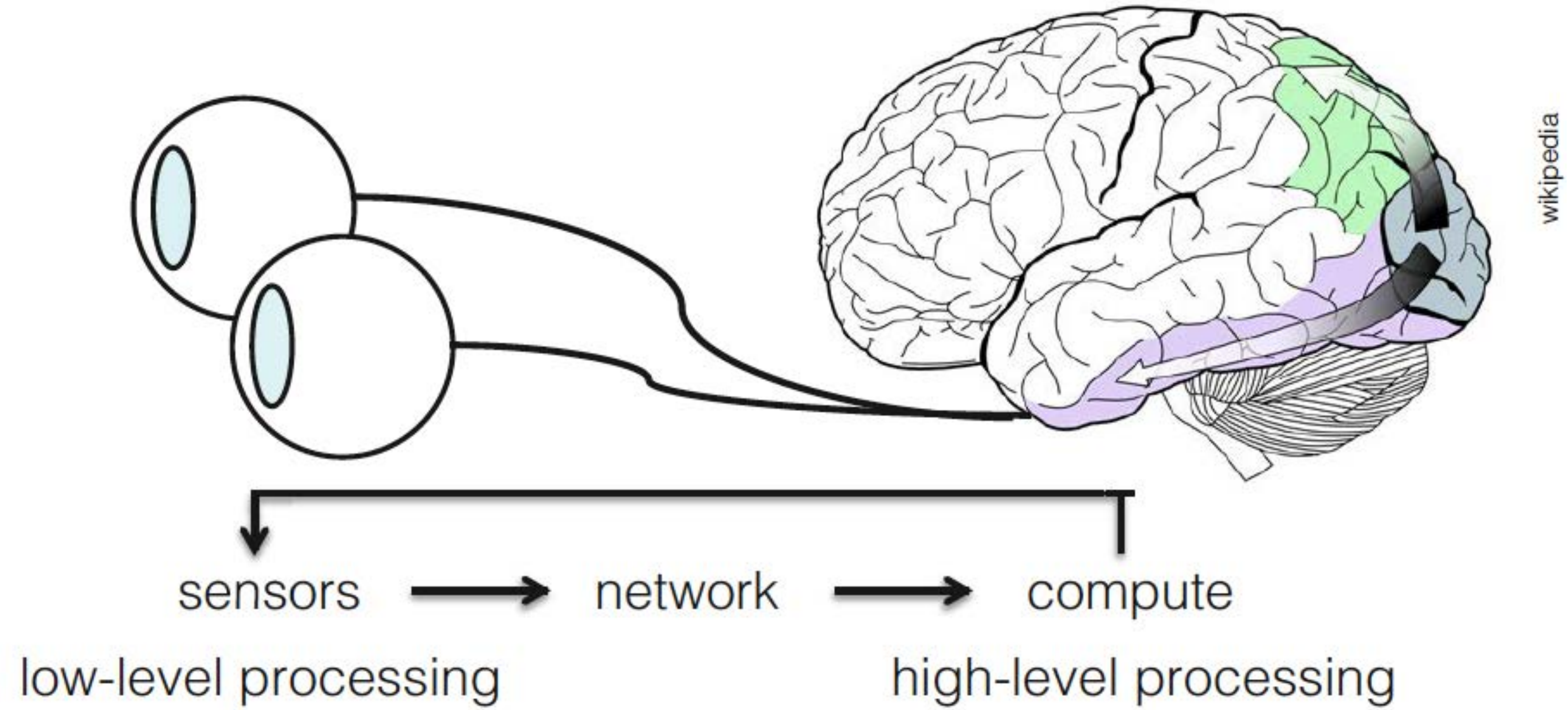
Example: Visual Simulation

Visual Simulation → **3D Graphics** → **HMD** → **Vision System** → **Brain**

Human-Machine Interface

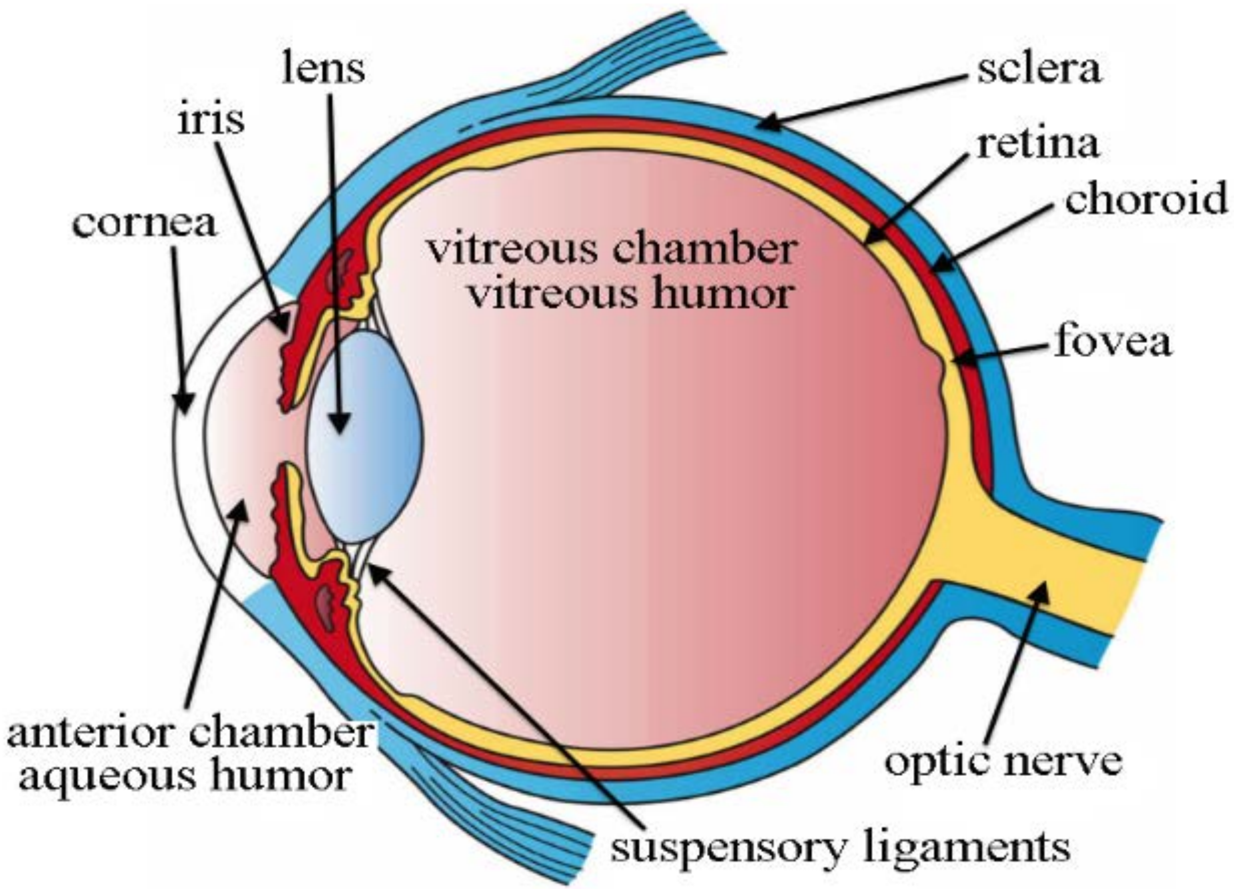

Sight

The Human Visual System



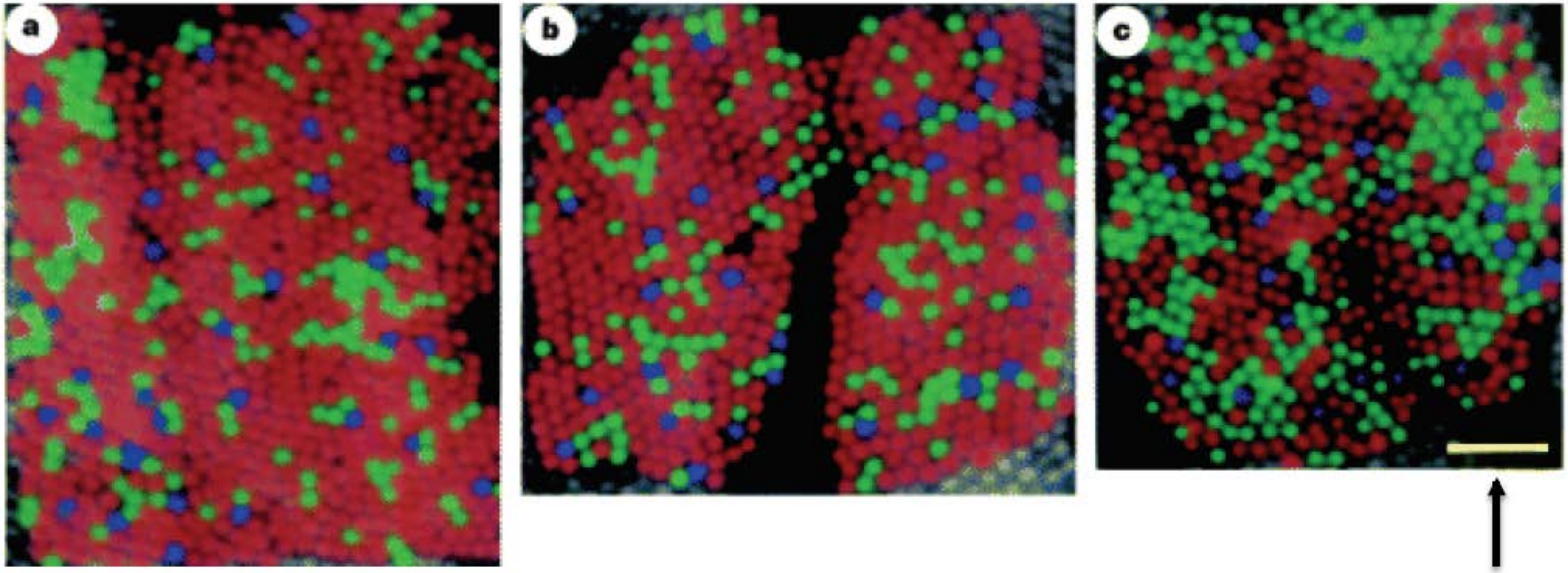
- Purpose is to convert visual input to signals in the brain

The Human Eye



- Light passes through cornea and lens onto retina
- Photoreceptors in retina convert light into electrochemical signals

Photoreceptors – Rods and Cones



Roorda & Williams, 1999, Nature

photoreceptors: 3 types of cones (color vision), rods (luminance only, night vision)

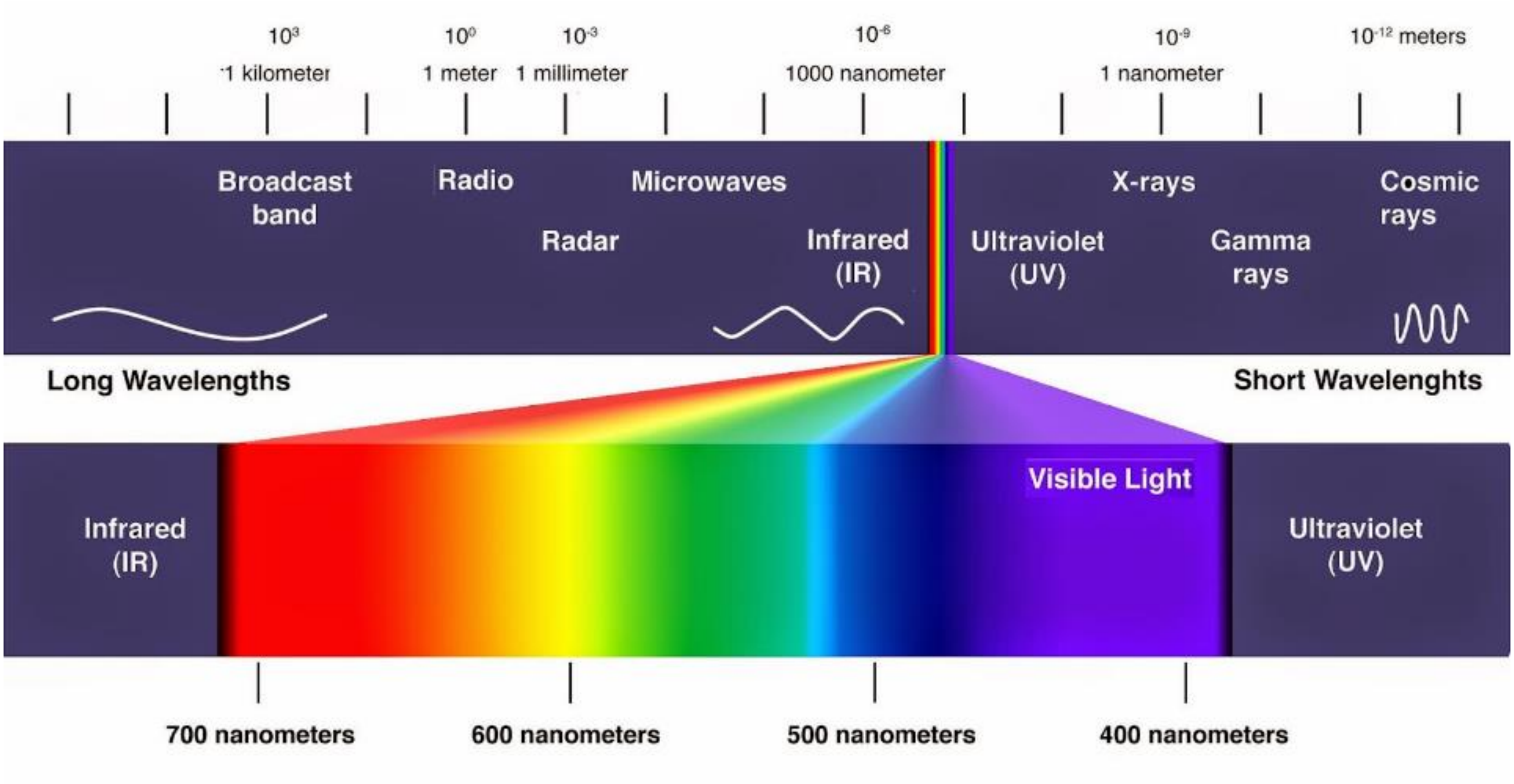
- Retina photoreceptors come in two types, Rods and Cones

Rods vs. Cones

- **RODS**
  - 125 million cells in retina
  - Concentrated on periphery of retina
  - No color detection
  - Most sensitive to light
  - Scotopic (night) vision
  - Provide peripheral vision, motion detection

- **CONES**
  - 4.5-6 million in retina
  - Responsible for color vision
  - Sensitive to red, blue, green light
  - Work best in more intense light

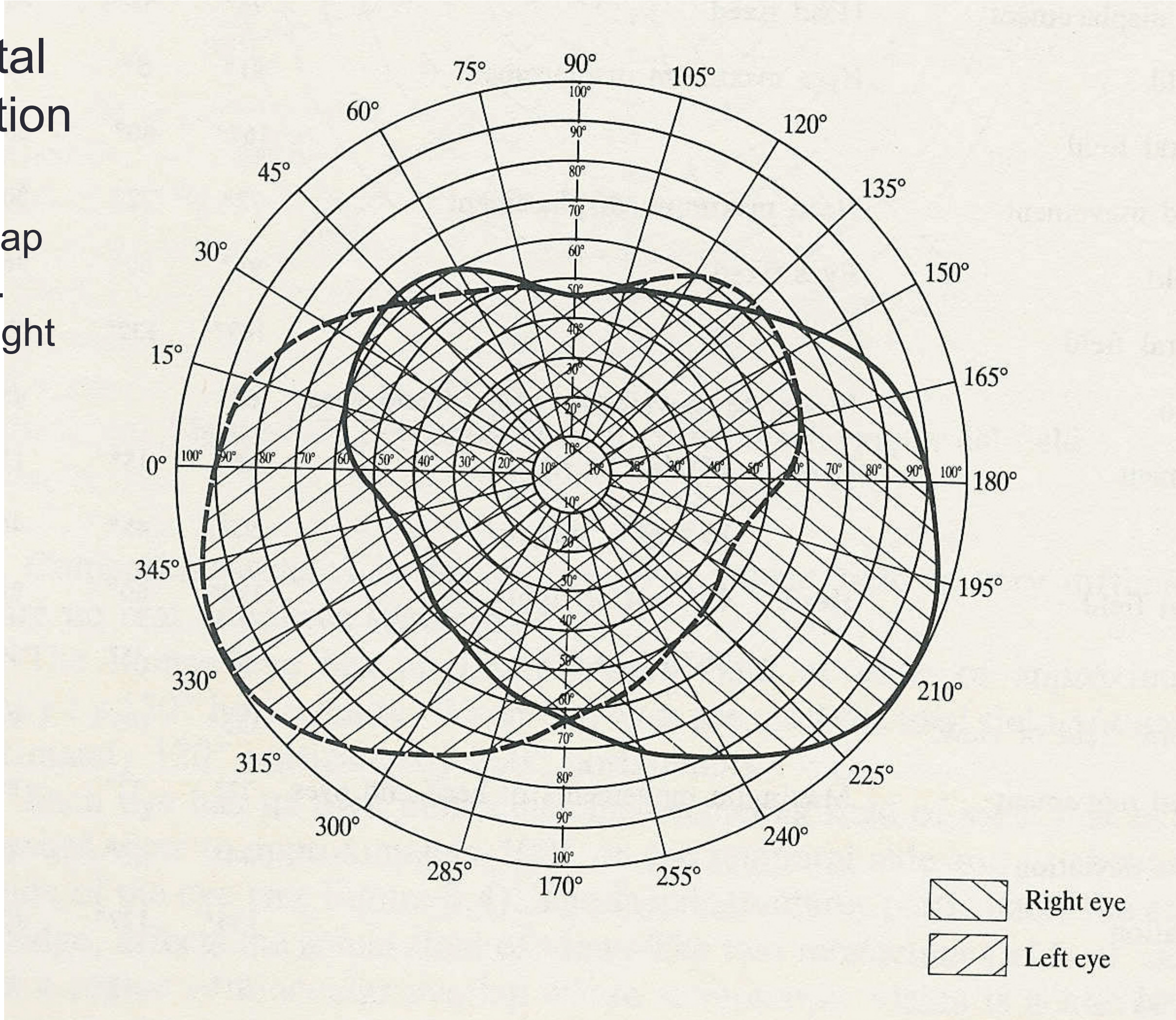
Colour Perception



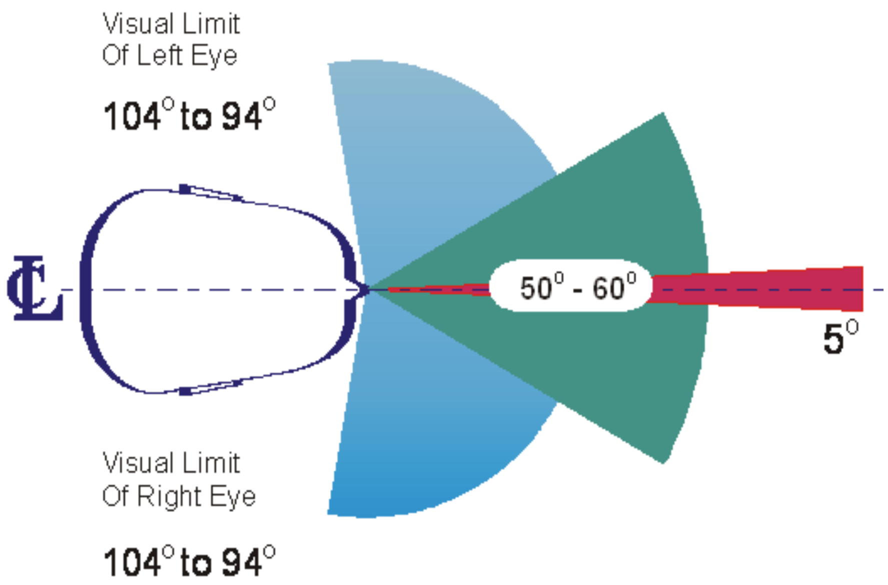
- Humans only perceive small part of electromagnetic spectrum

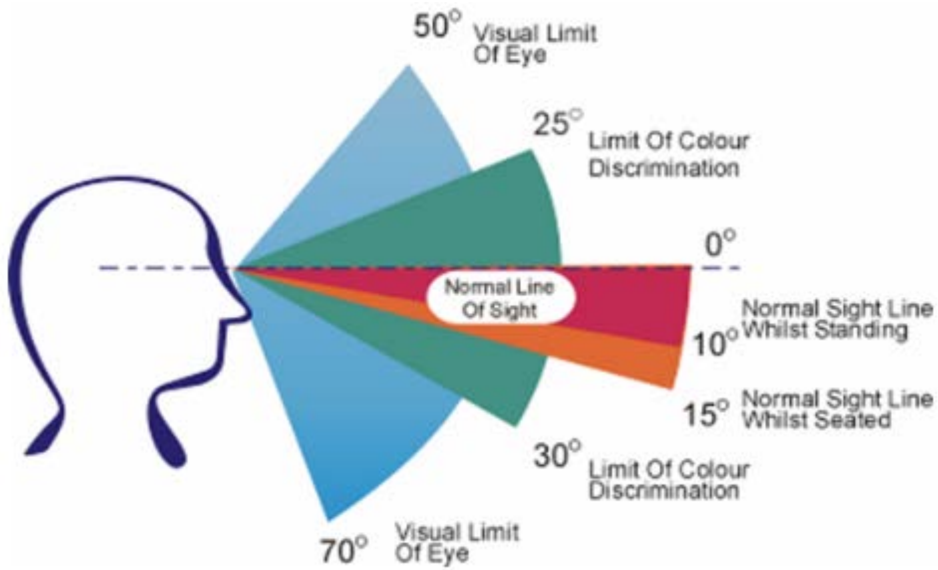
Visual field of view (FOV)

- almost 200° in horizontal and 120° vertical direction
- Fields of the both eyes overlap in the center area (ca. 100°). This enables stereoscopic sight (each eye sees a slightly different image)



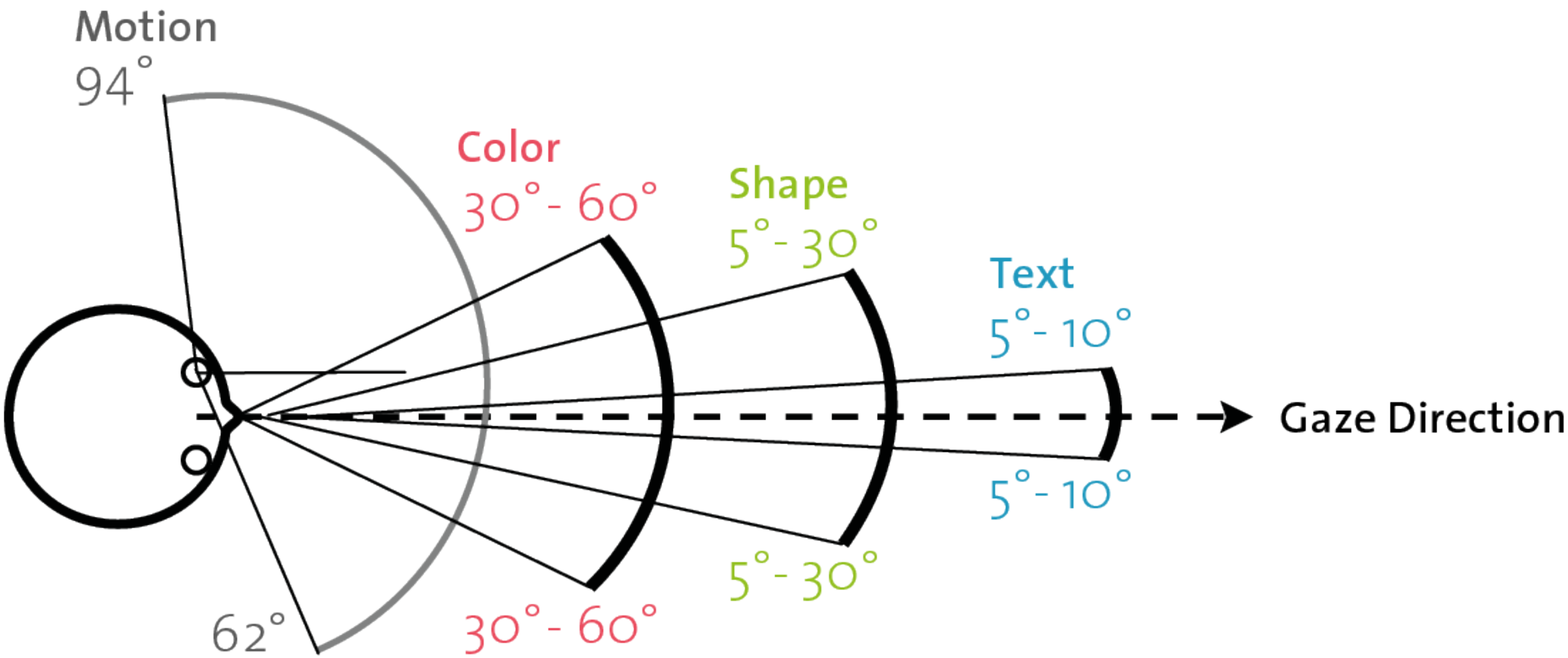
Horizontal and Vertical FOV





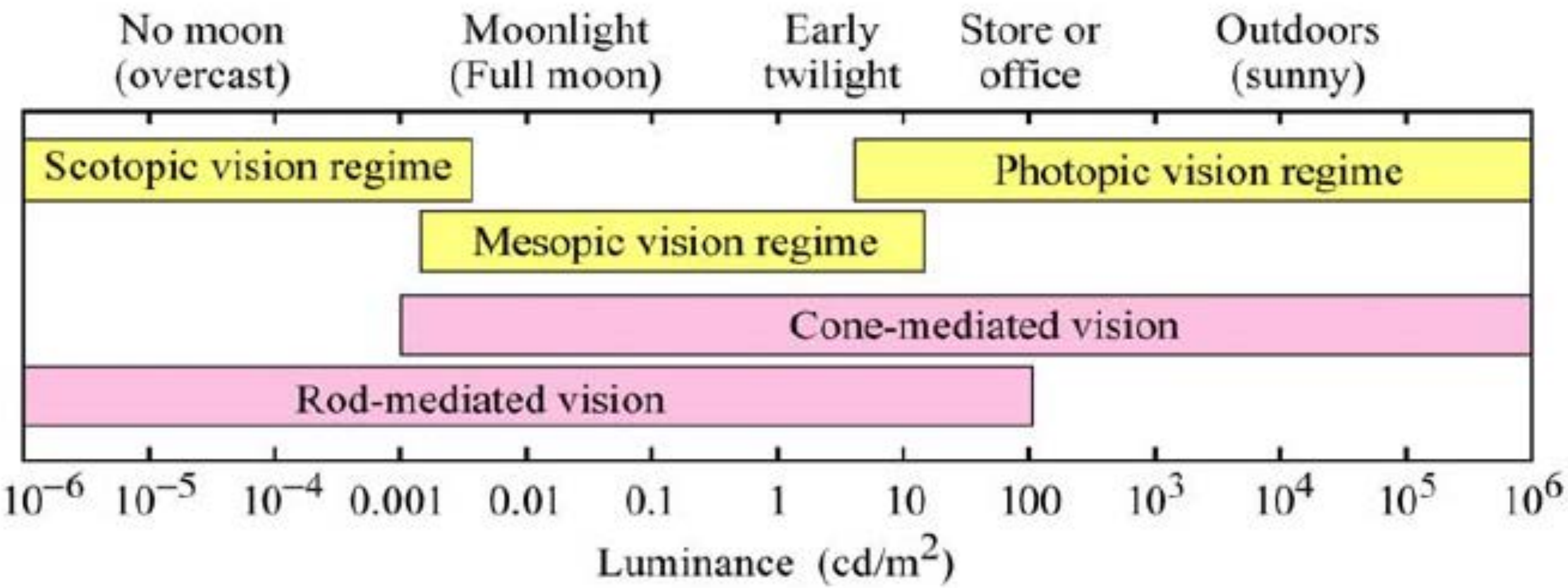
- Humans can see ~135^o vertical (60^o above, 75^o below)
- See up to ~ 210^o horizontal FOV, ~ 115^o stereo overlap
- Colour/stereo in centre, Black & White/mono in periphery

Types of Visible Perception Possible



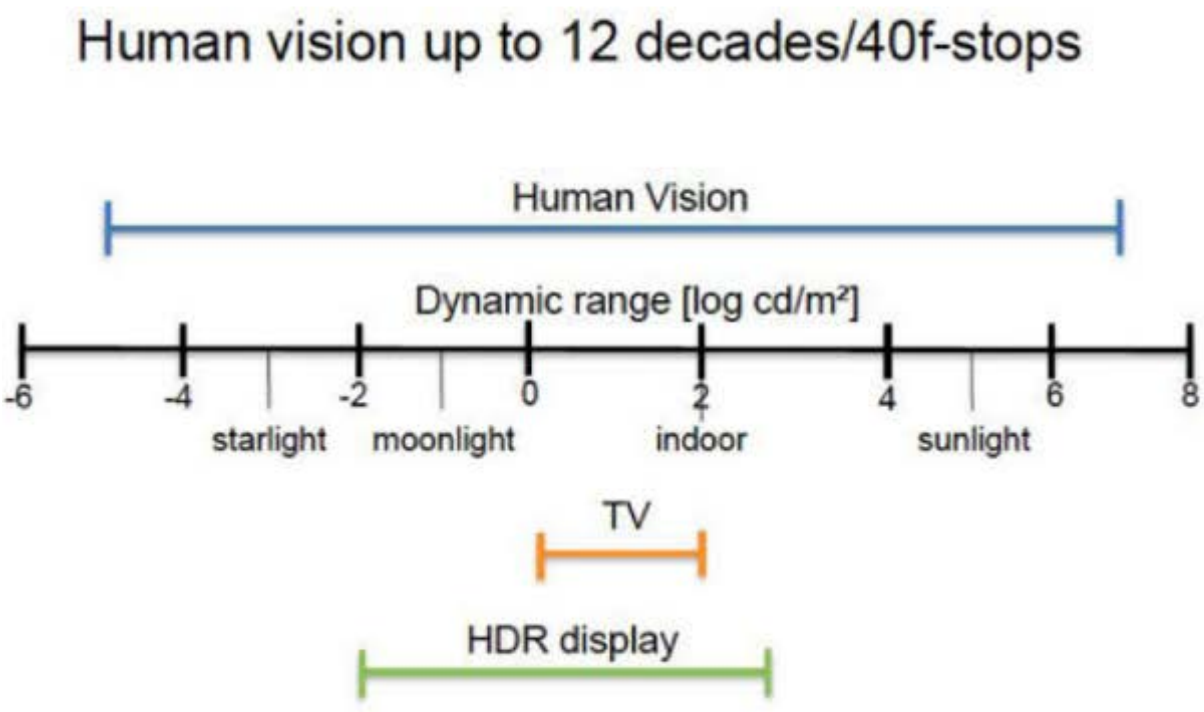
- As move further from fovea, vision becomes more limited

Dynamic Range



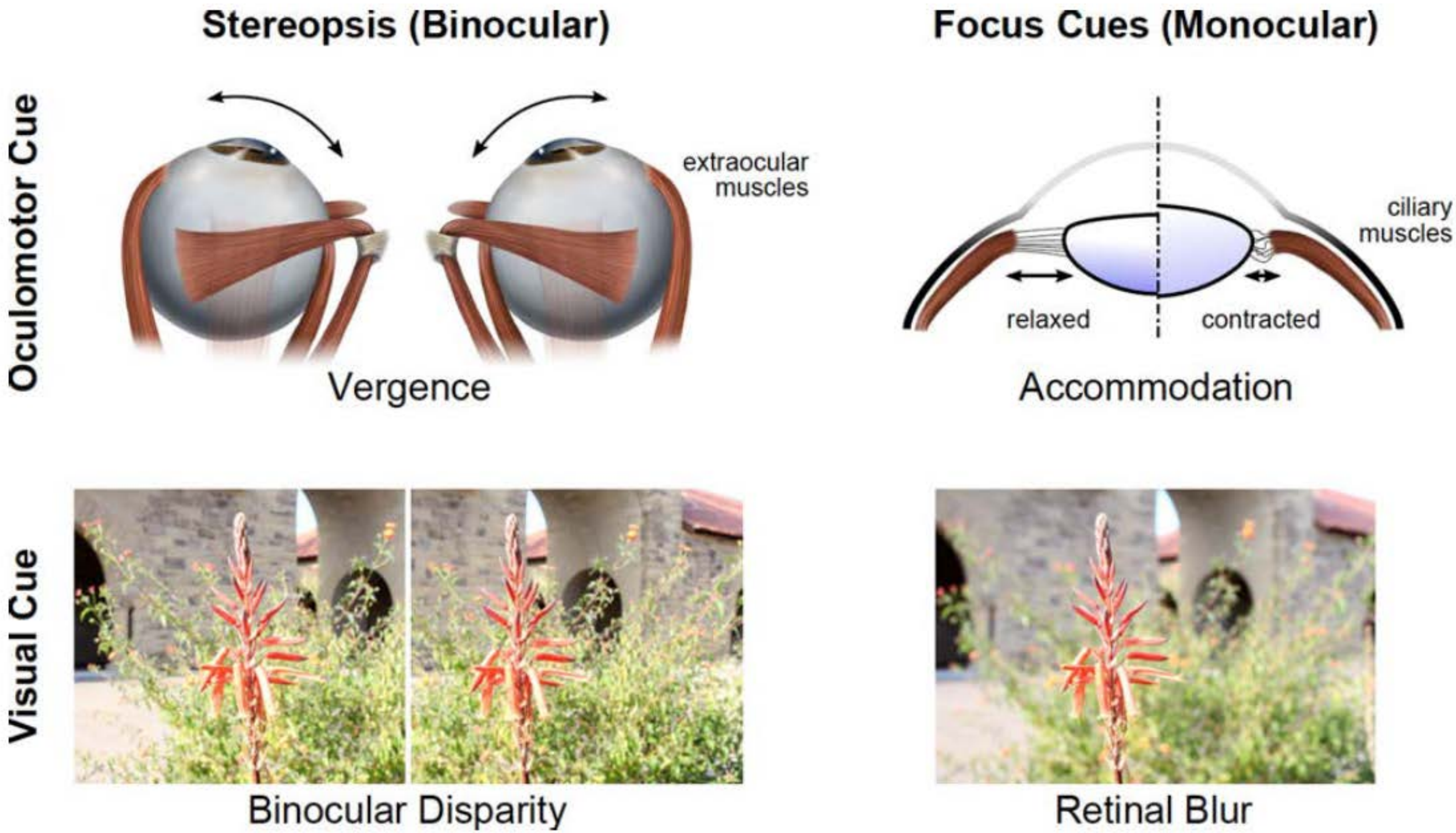
- Rods respond to low Luminance light, Cones to bright light

Comparing to Displays



- Human vision has far higher dynamic range than any available display technology
  - 40 f-stops, cf. 17 f-stops for HDR display

Vergence + Accommodation



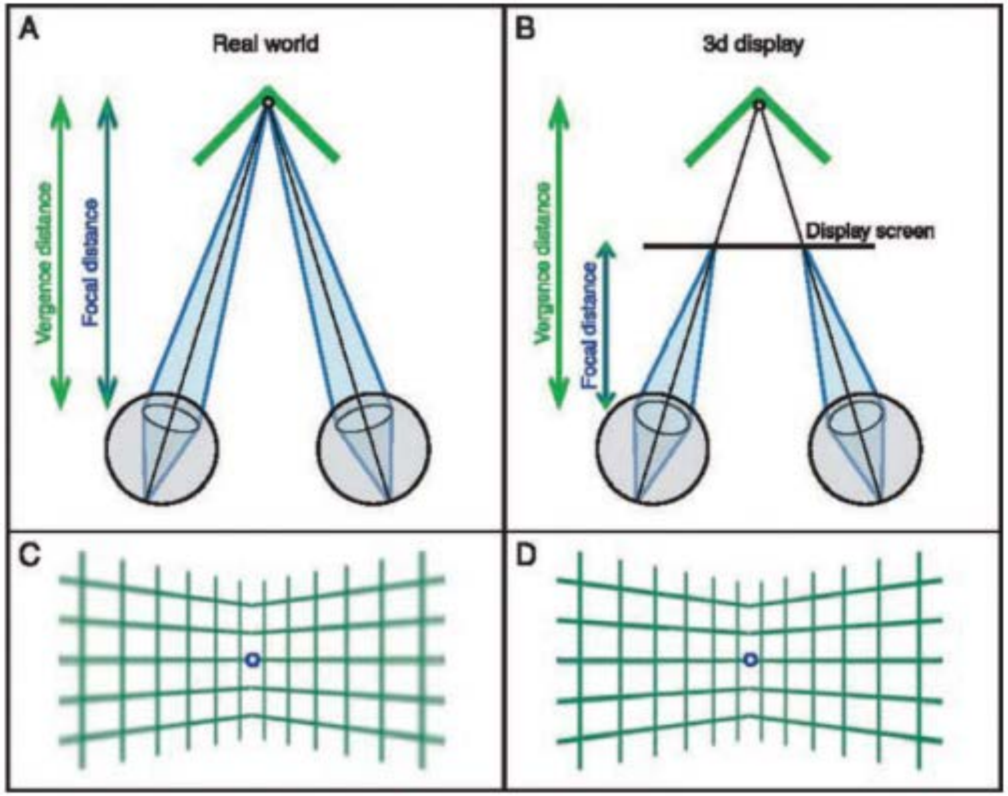
Vergence/Accommodation Demo

- https://www.youtube.com/watch?v=p_xLO7yxgOk

2'05"

Vergence-Accommodation Conflict

Marty Banks, UC Berkeley

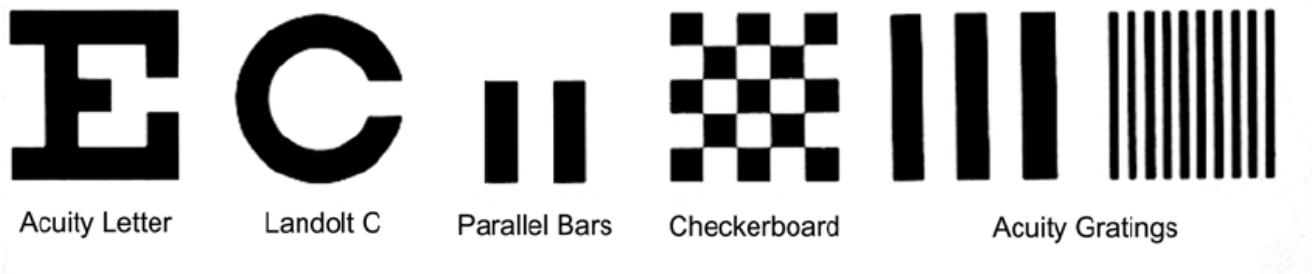


effects

- visual discomfort
- visual fatigue
- nausea
- diplopic vision
- eyestrain
- compromised image quality
- pathologies in developing visual system
- …

- Looking at real objects, vergence and focal distance match
- In Virtual Reality, vergence and accommodation can miss-match
  - Focusing on HMD screen, but accommodating for virtual object behind screen

Visual Acuity

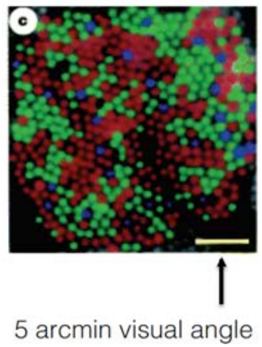


Visual Acuity Test Targets

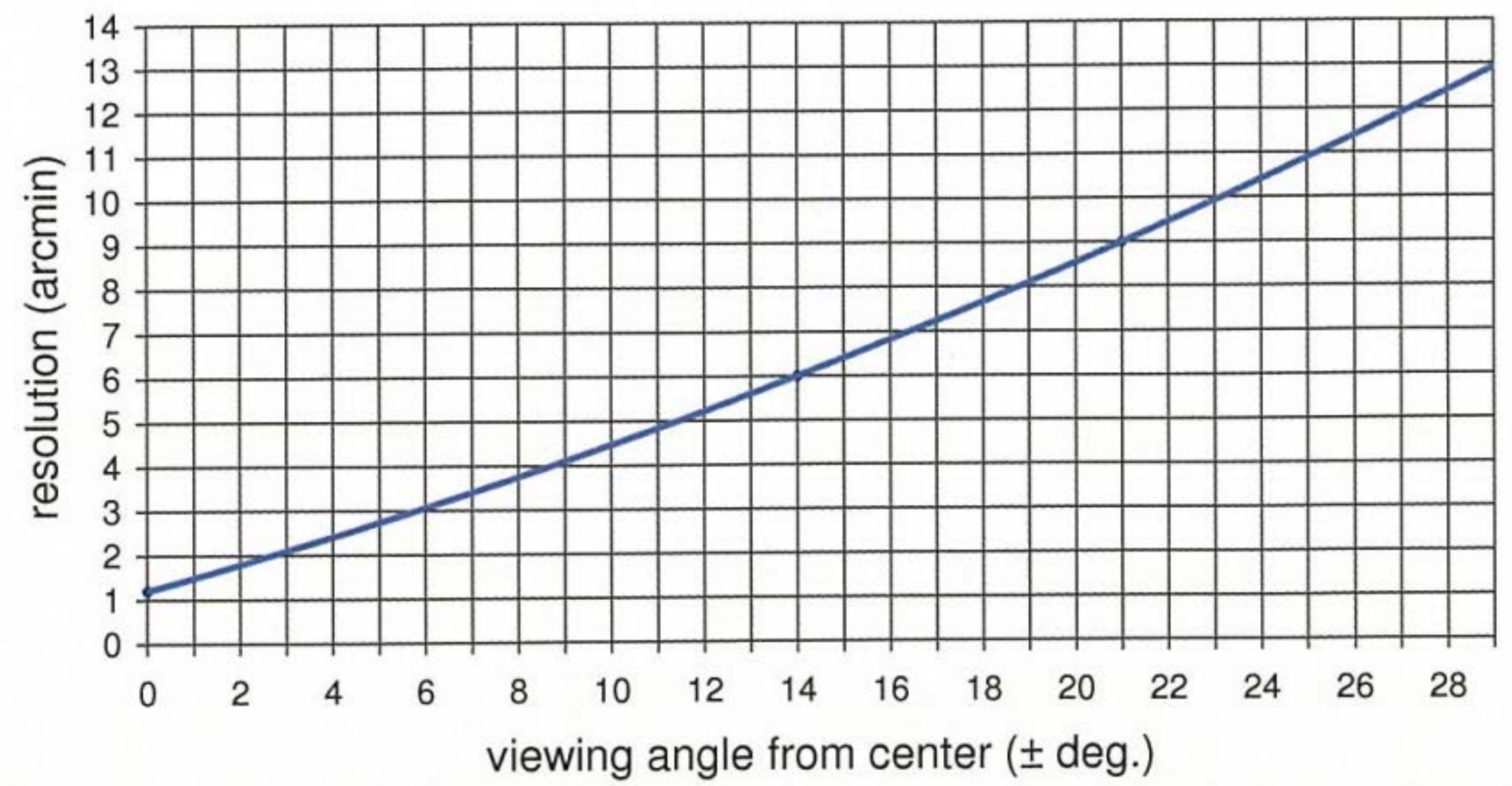
- Ability to resolve details
- Several types of visual acuity
  - detection, separation, etc
- Normal eyesight can see a 50 cent coin at 80m
  - Corresponds to 1 arc min (1/60th of a degree)
  - Max acuity = 0.4 arc min

Roorda & Williams, 1999, Nature

each photorecepter
~ 1 arc min (1/60 of a degree)



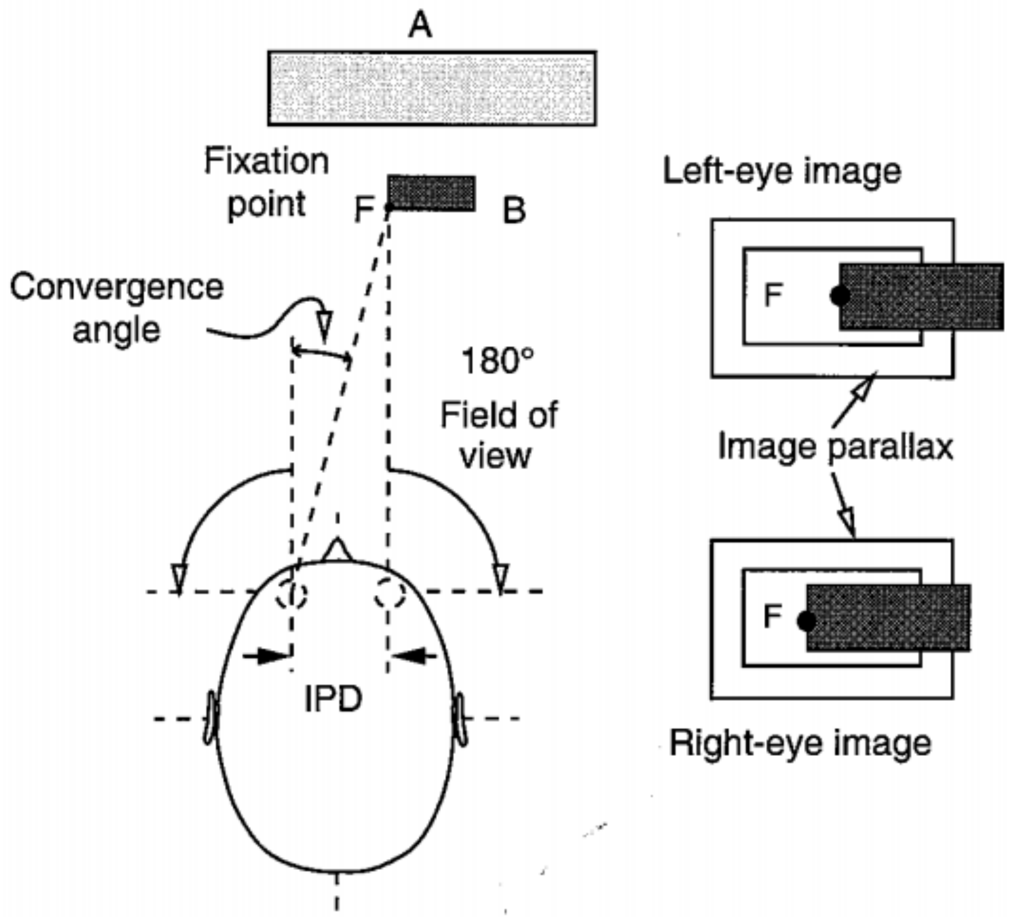
Resolution of the Eye

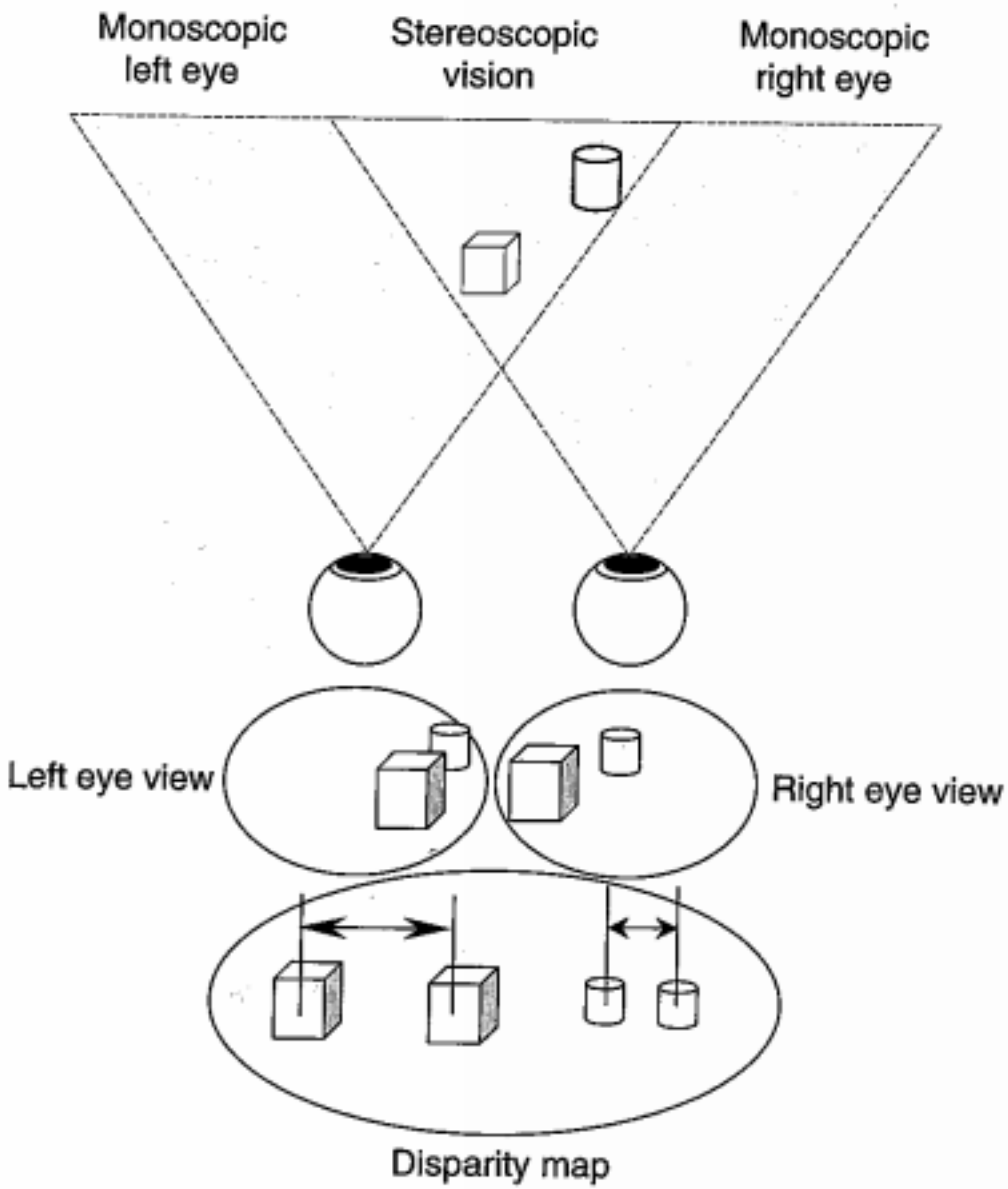


- Decreases away from the fovea
  - Maximum resolution of 1 arcmin – spot of 6×10^{-6} m size on retina

Stereo Perception/Stereopsis

- Eyes separated by IPD
  - Inter pupillary distance
  - 5 – 7.5cm (average. 6.5cm)
- Each eye sees diff. image
  - Separated by image parallax
- Images fused to create 3D stereo view





Monoscopic left eye
Stereoscopic vision
Monoscopic right eye
Left eye view
Right eye view
Disparity map

Depth Perception

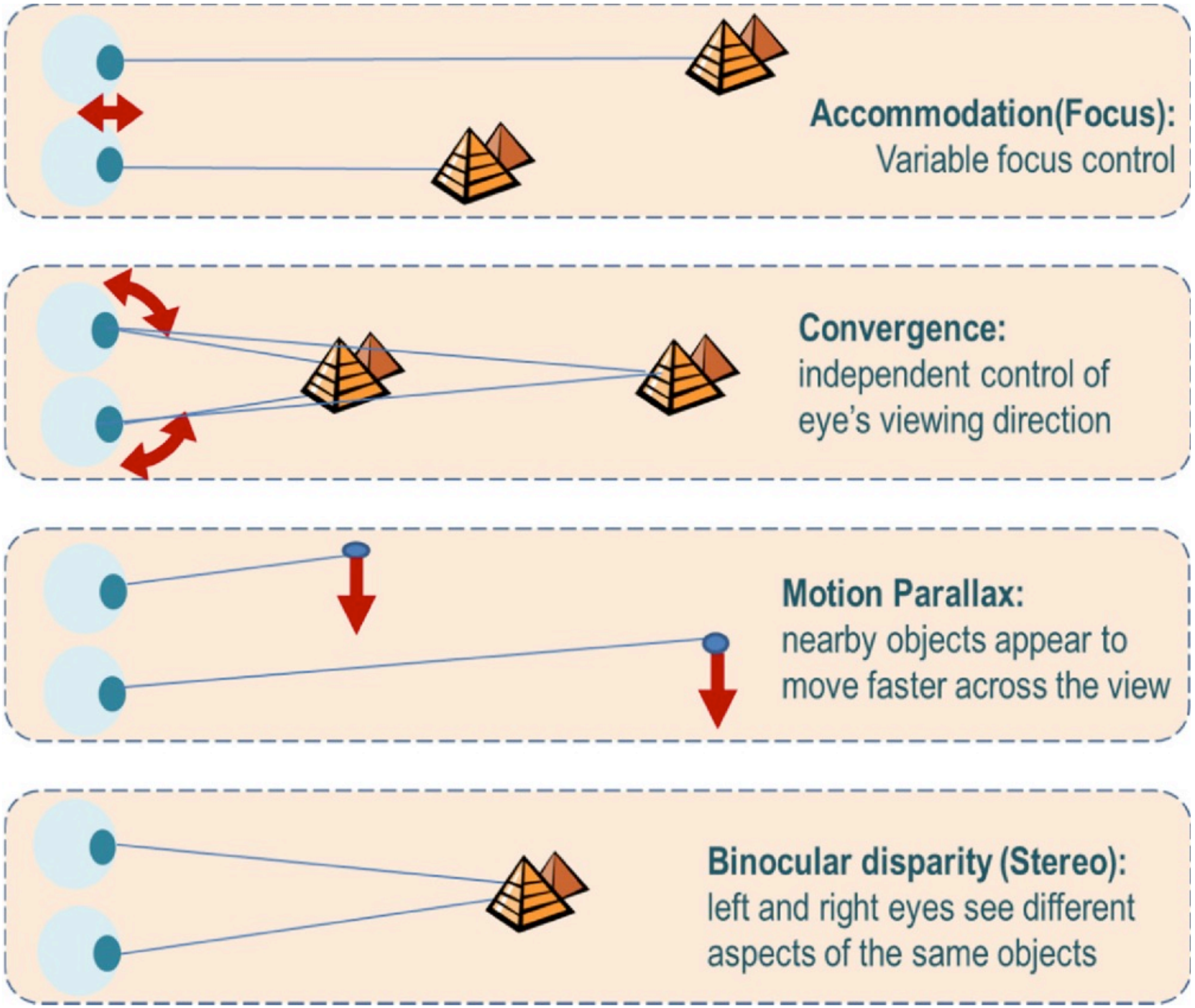
- The visual system uses a range of different Stereoscopic and Monocular cues for depth perception

Stereoscopic	Monocular
eye convergence angle disparity between left and right images diplopia	eye accommodation perspective atmospheric artifacts (fog) relative sizes image blur occlusion motion parallax shadows texture

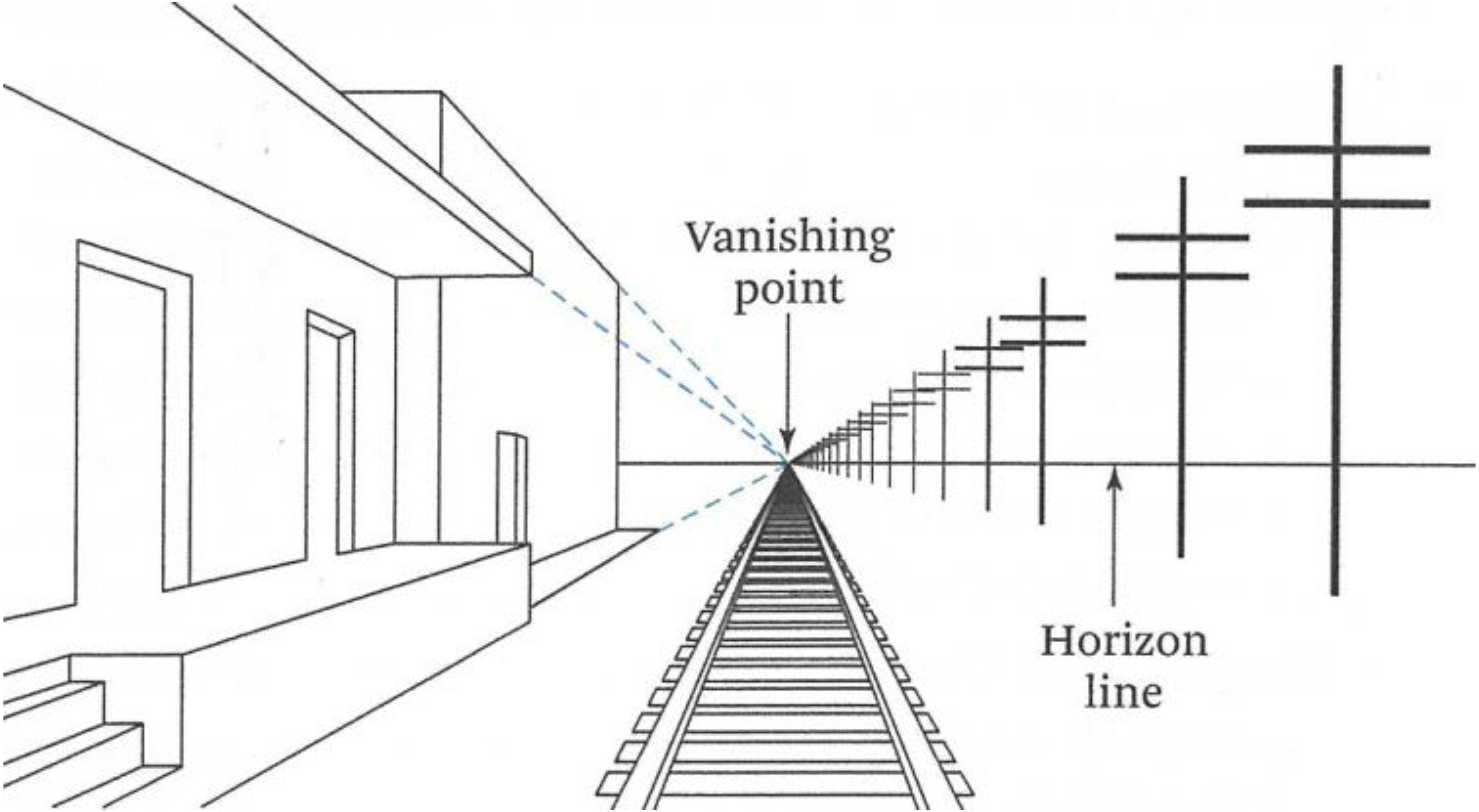
Parallax can be more important for depth perception!

Stereoscopy is important for size and distance evaluation

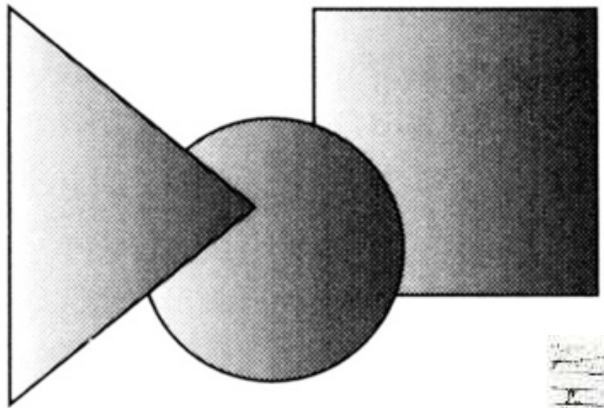
More Depth Cues



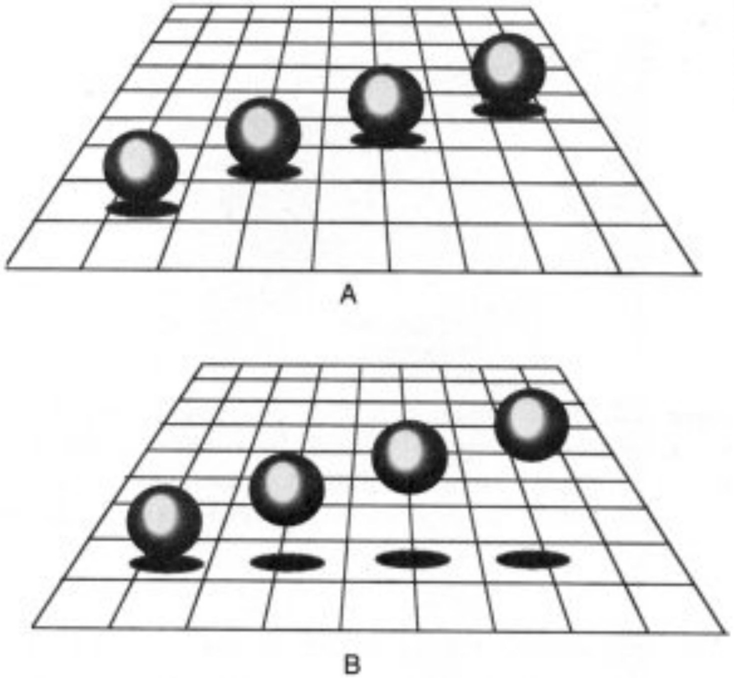
Example: Perspective Cues



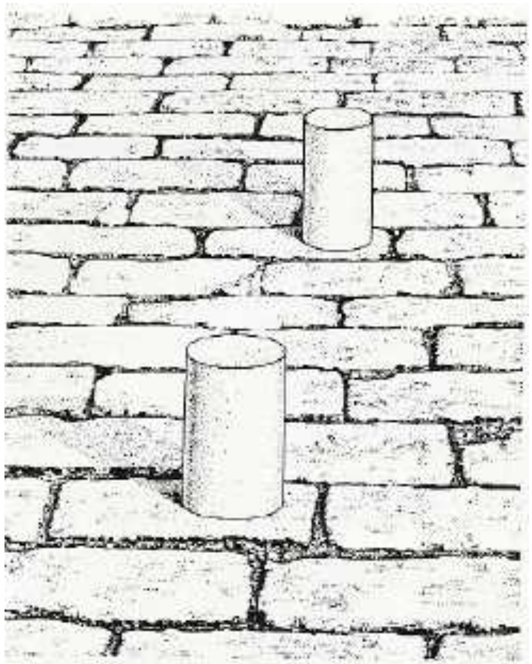
More Examples



Occlusion

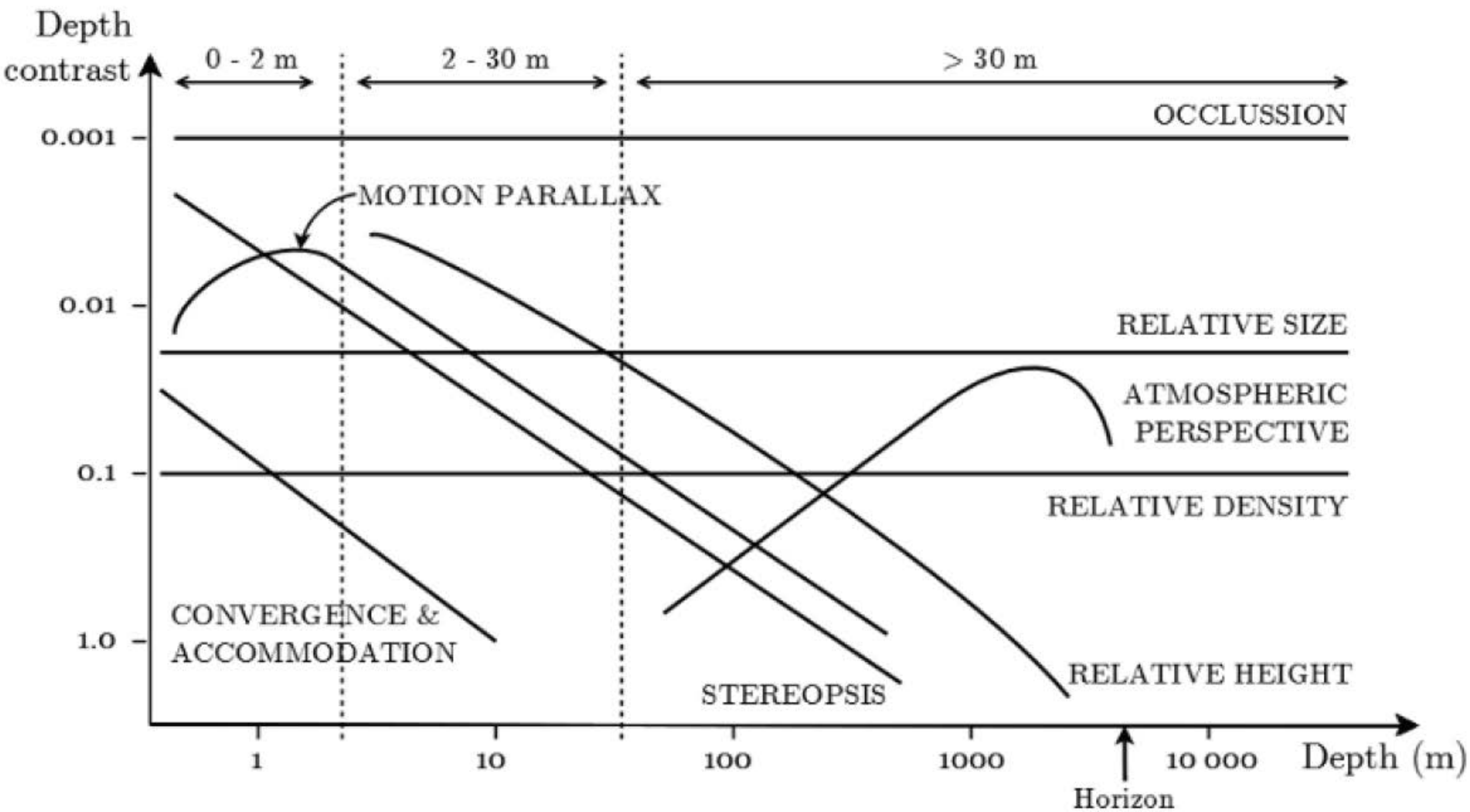


Shadows



Texture Gradient

Depth Perception Distances



Cutting & Vishton, 1995

Fooling Depth Perception

- https://www.youtube.com/watch?v=p-eZcHPp7Go 3'05"

Properties of the Human Visual System

- visual acuity: 20/20 is ~1 arc min
- field of view: ~200° monocular, ~120° binocular, ~135° vertical
- resolution of eye: ~576 megapixels
- temporal resolution: ~60 Hz (depends on contrast, luminance)
- dynamic range: instantaneous 6.5 f-stops, adapt to 46.5 f-stops
- colour: everything in CIE xy diagram
- depth cues in 3D displays: vergence, focus, (dis)comfort
- accommodation range: ~8cm to ∞, degrades with age

The Perfect Retina Display

- A HMD capable of creating images indistinguishable from reality would need to match the properties of the eye:
  - FOV: 200-220° x 135° needed (both eyes)
    - 120° stereo overlap
  - Acuity: ~0.4 arc min ➔ 1 pixel/0.4 arc min ≈ 150 pix/deg (PPD)
  - Pixel Resolution: ~30,000 x 20,000 pixels
    - 200*60°/0.4 = 30,000, 135*60°/0.4 = 20,250
  - Pixels/inch: > 2190 PPI @ 100mm (depends on distance to screen)
  - Update rate: 60 Hz
- The biggest challenge: bandwidth
  - compress and transmit huge amount of data
  - drive and operate display pixels

Comparison between Eyes and HMD

	Human Eyes	HTC Vive
FOV	200° x 135°	110° x 110°
Stereo Overlap	120°	110°
Resolution	30,000 x 20,000	2,160 x 1,200
PPD	150	20
Pixels/inch	>2190 (100mm to screen)	456
Update	60 Hz	90 Hz

See http://doc-ok.org/?p=1414
http://www.clarkvision.com/articles/eye-resolution.html
http://wolfcrow.com/blog/notes-by-dr-optoglass-the-resolution-of-the-human-eye/

Recent development: VARJO headset

- Aims at human eye resolution
- High resolution at the fovea, less in the peripheral
- Eye tracking used to locate gaze direction

VR-2 Pro

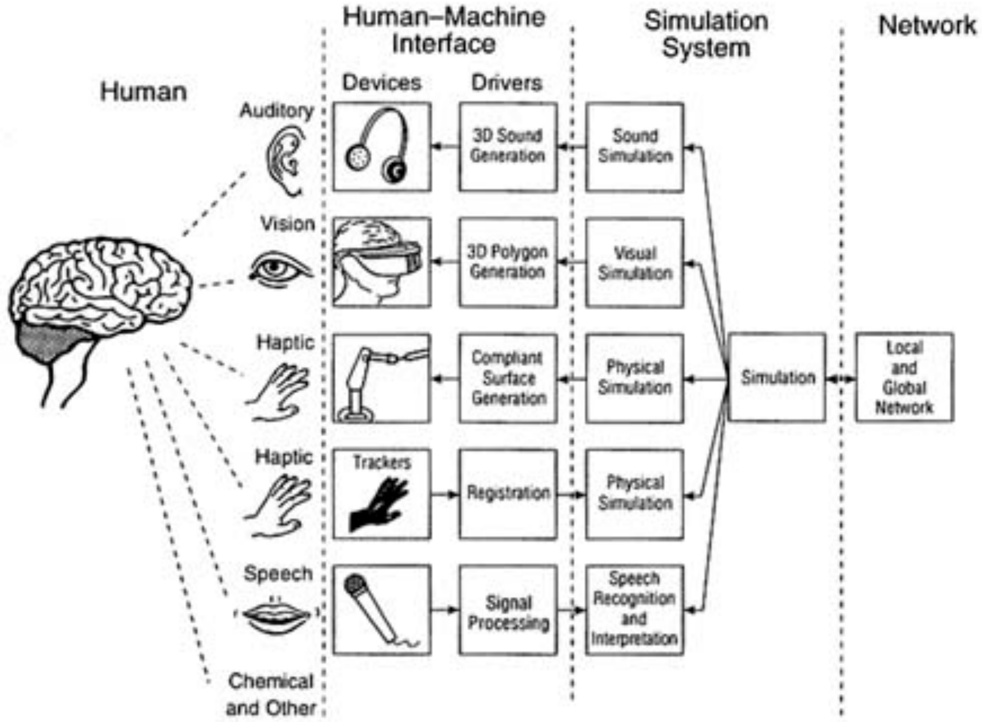
- https://varjo.com/products/vr-2-pro/
- 1440×1600 per eye (standard screen) FOV 87° ≈ 22 PPD
- 1920 x 1080 pix micro-display, following the eye gaze
  - resolution of over 60 PPD

- https://skarredghost.com/2020/01/31/varjo-vr2-hands-on-review/

VR TECHNOLOGY

Using Technology to Stimulate Senses

- Simulate output
  - E.g. simulate real scene
- Map output to devices
  - Graphics to HMD
- Use devices to stimulate the senses
  - HMD stimulates eyes



Example: Visual Simulation

Visual Simulation → **3D Graphics** → **HMD** → **Vision System** → **Brain**

Human-Machine Interface

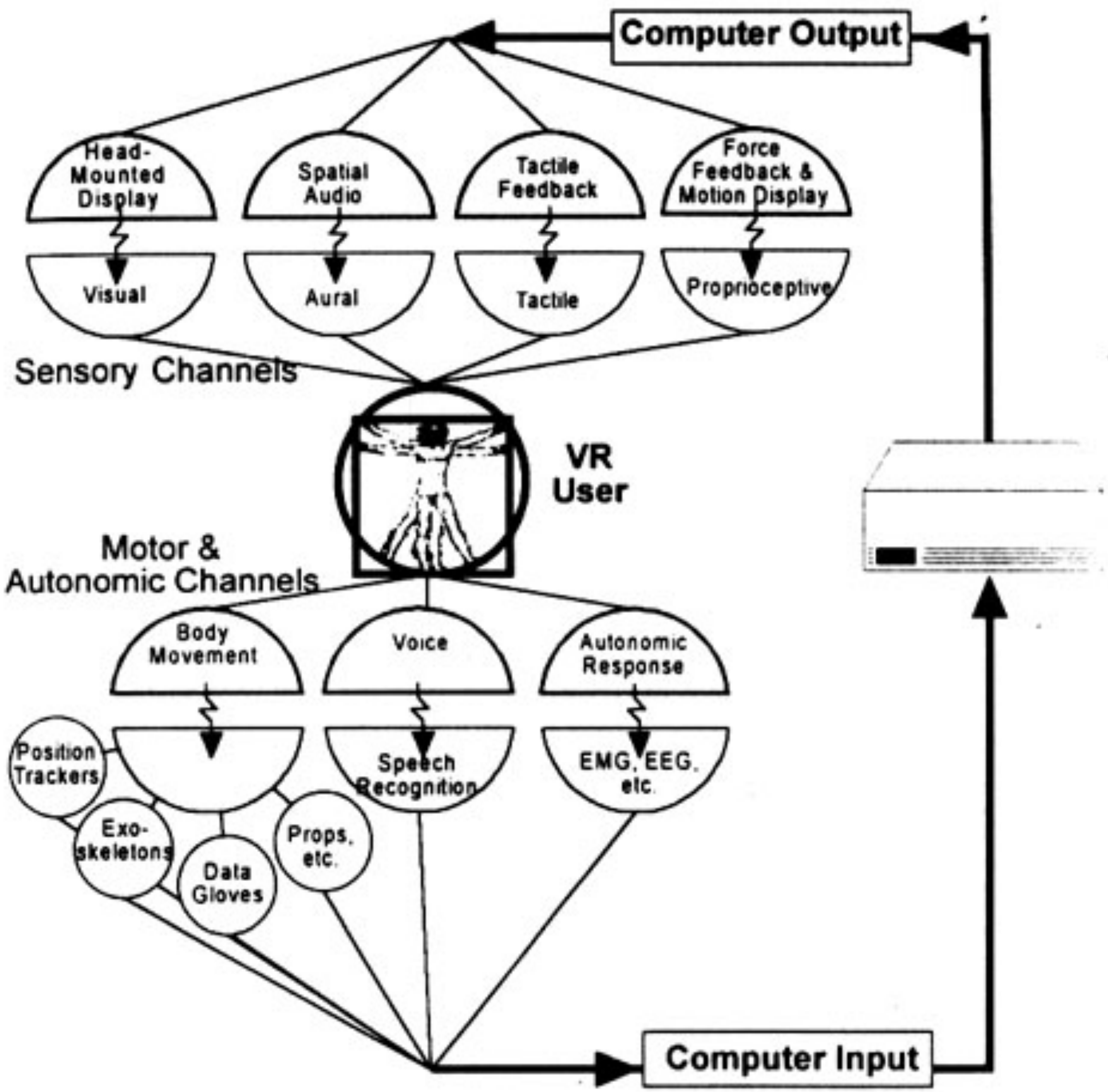
Key Technologies for VR System

- Visual Display
  - Stimulate visual sense
- Audio/Tactile Display
  - Stimulate hearing/touch
- Tracking
  - Changing viewpoint
  - User input
- Input Devices
  - Supporting user interaction

Mapping Between Input and Output

Input

Output

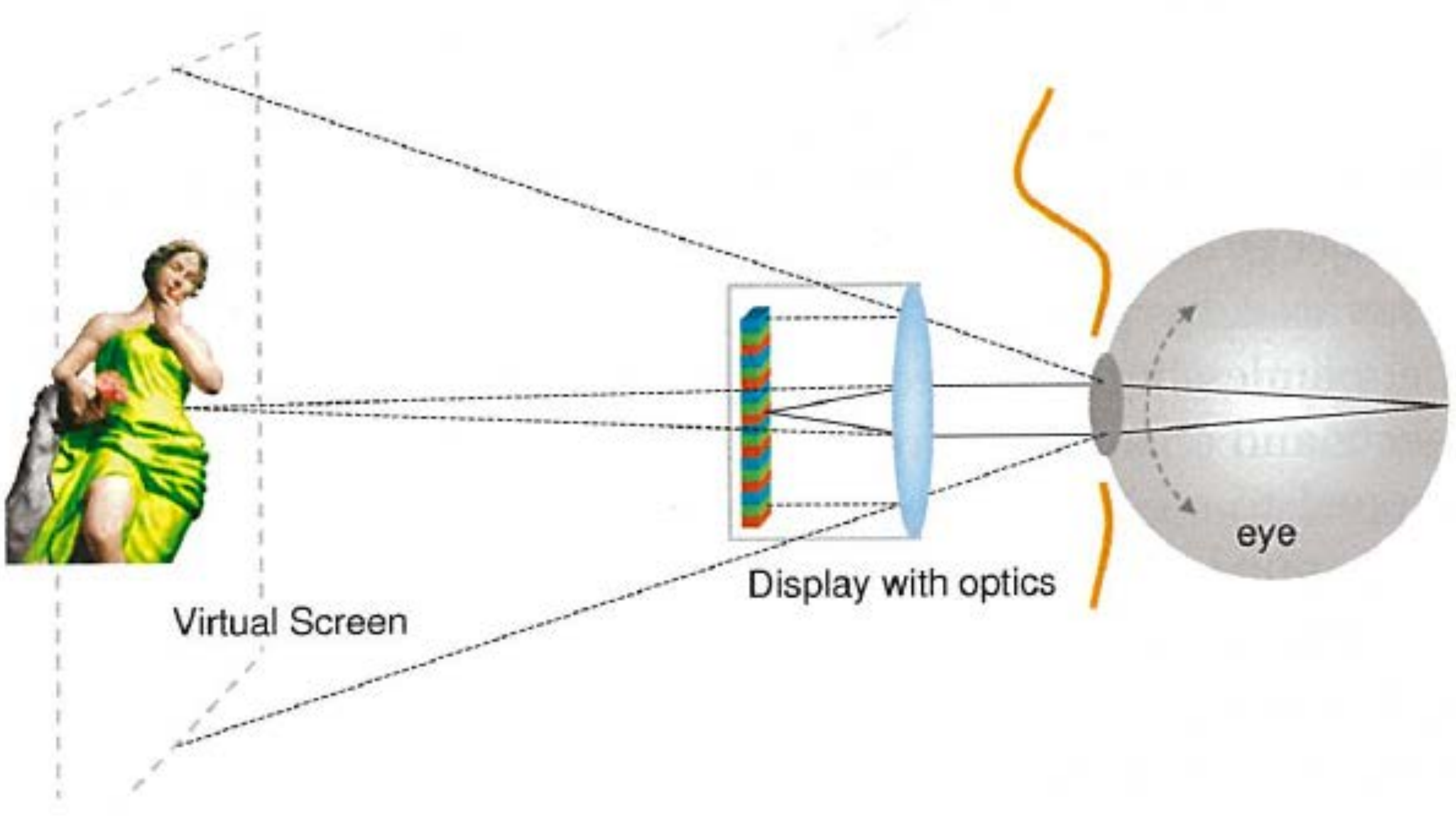


VISUAL DISPLAY

Creating an Immersive Experience

- Head Mounted Display
  - Immerse the eyes
- Projection/Large Screen
  - Immerse the head/body
- Future Technologies
  - Neural implants
  - Contact lens displays, etc

HMD Basic Principles

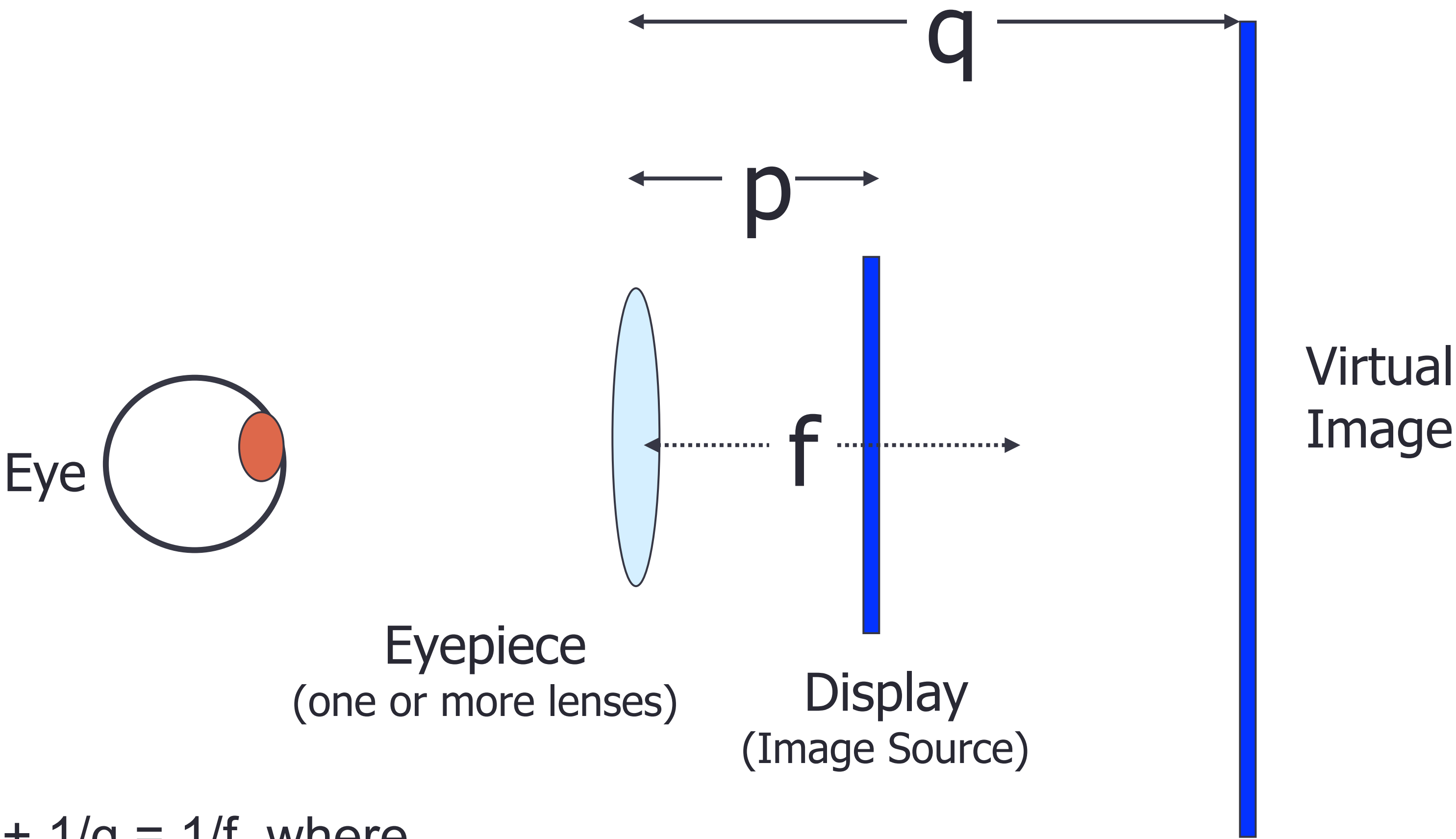


- Use display with optics to create illusion of virtual screen

Key Properties of HMDs

- Lens
  - Focal length, Field of View
  - Occularity, Interpupillary distance
  - Eye relief, Eye box
- Display
  - Resolution, contrast
  - Power, brightness
  - Refresh rate
- Ergonomics
  - Size, weight
  - Wearability

Simple Magnifier HMD Design



$1/p + 1/q = 1/f$ where

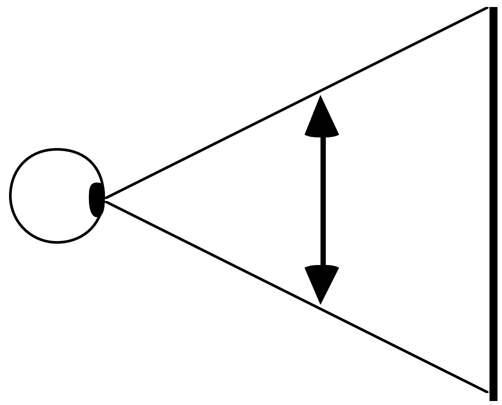
p = object distance (distance from image source to eyepiece)

q = image distance (distance of image from the lens)

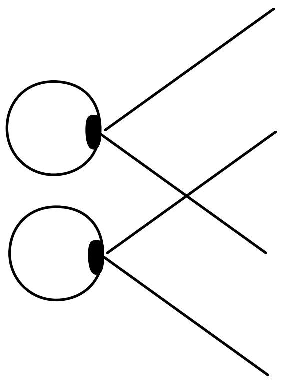
f = focal length of the lens

Field of View

Monocular FOV is the angular subtense (usually expressed in degrees) of the displayed image as measured from the pupil of one eye.



Total FOV is the total angular size of the displayed image visible to both eyes.



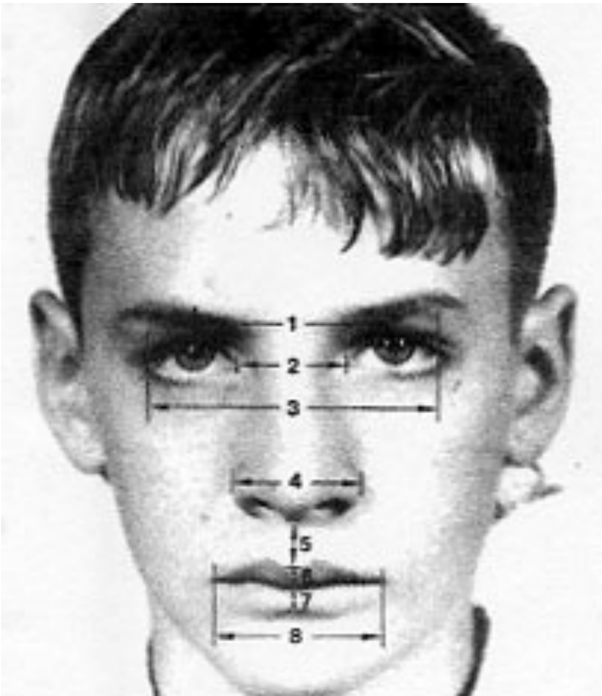
Binocular(or stereoscopic) FOV refers to the part of the displayed image visible to both eyes.

FOV may be measured horizontally, vertically or diagonally.

Ocularity

- **Monocular** - HMD image goes to only one eye.
- **Bioccular** - Same HMD image to both eyes.
- **Binocular (stereoscopic)** - Different but matched images to each eye.

Interpupillary Distance (IPD)

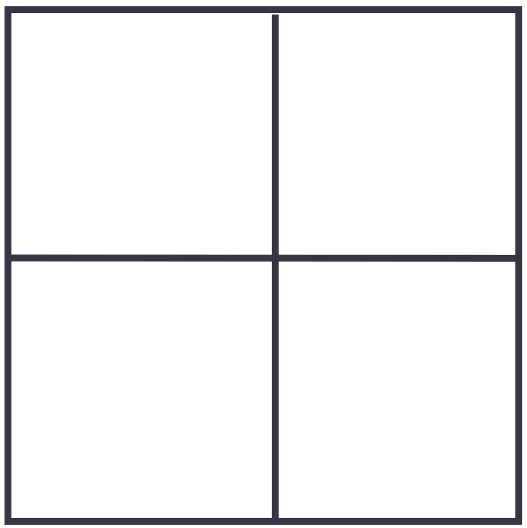


Interpupillary Distance Setting

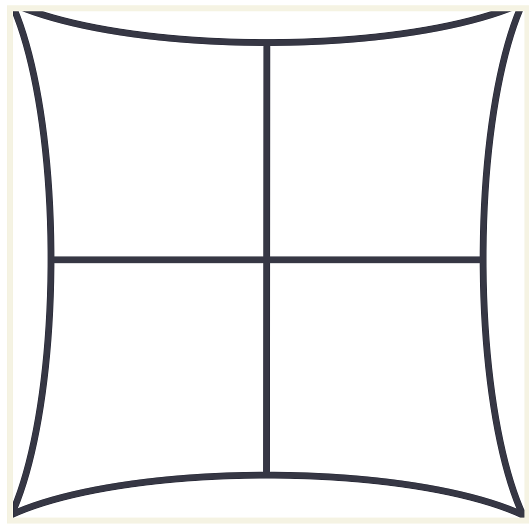
Figure 5

- IPD is the horizontal distance between a user's eyes.
- IPD is the distance between the two optical axes in a binocular view system.

Distortion in Lens Optics

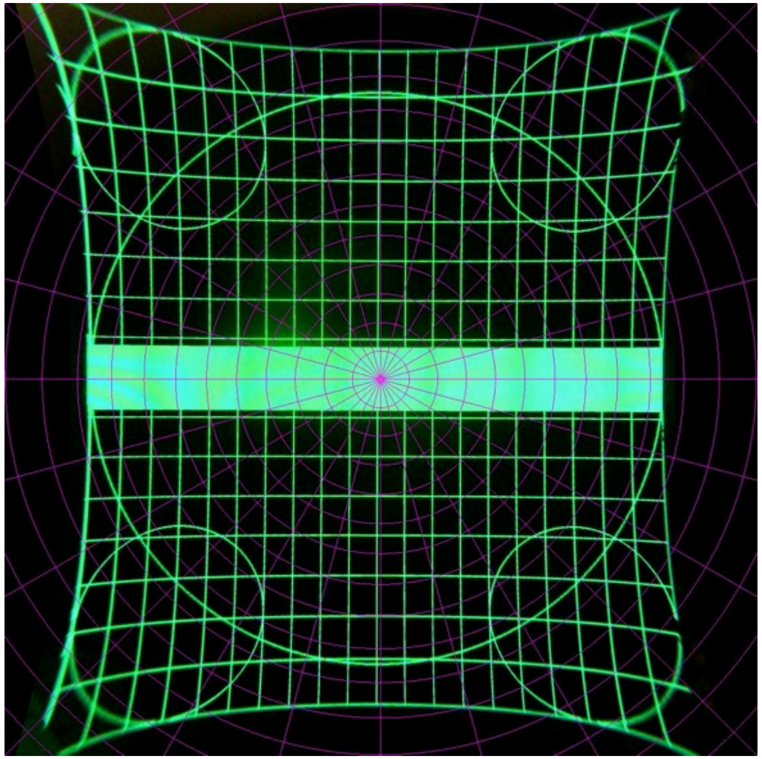


A rectangle

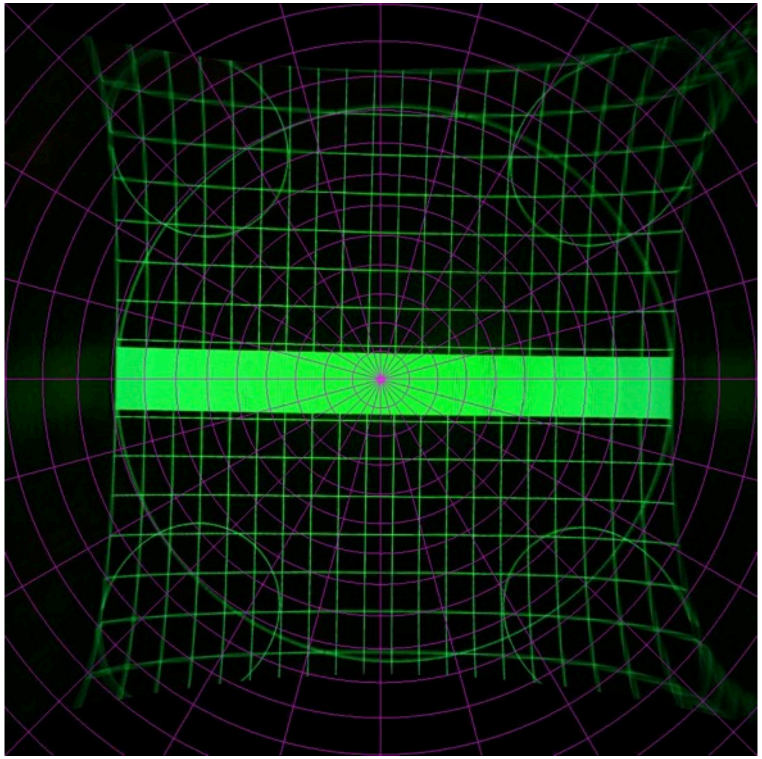


Maps to this

Example Distortion

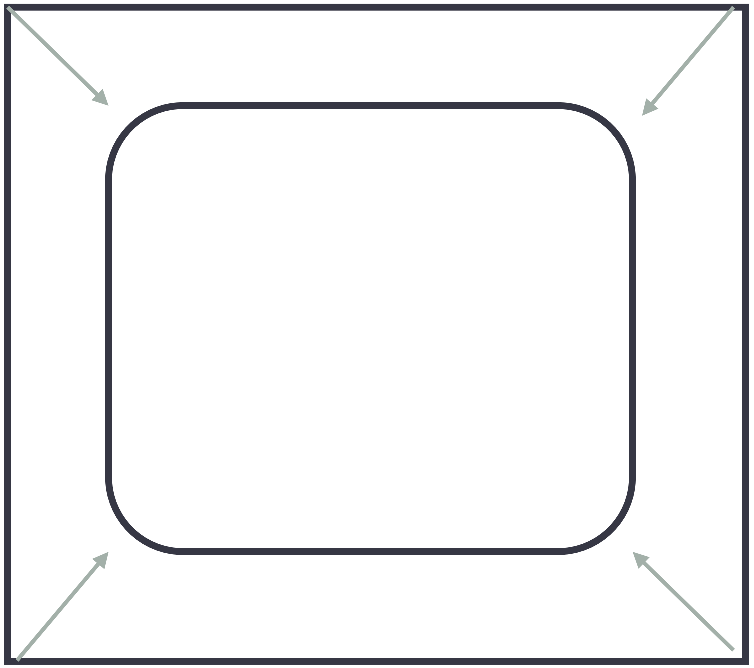


Oculus Rift DK2



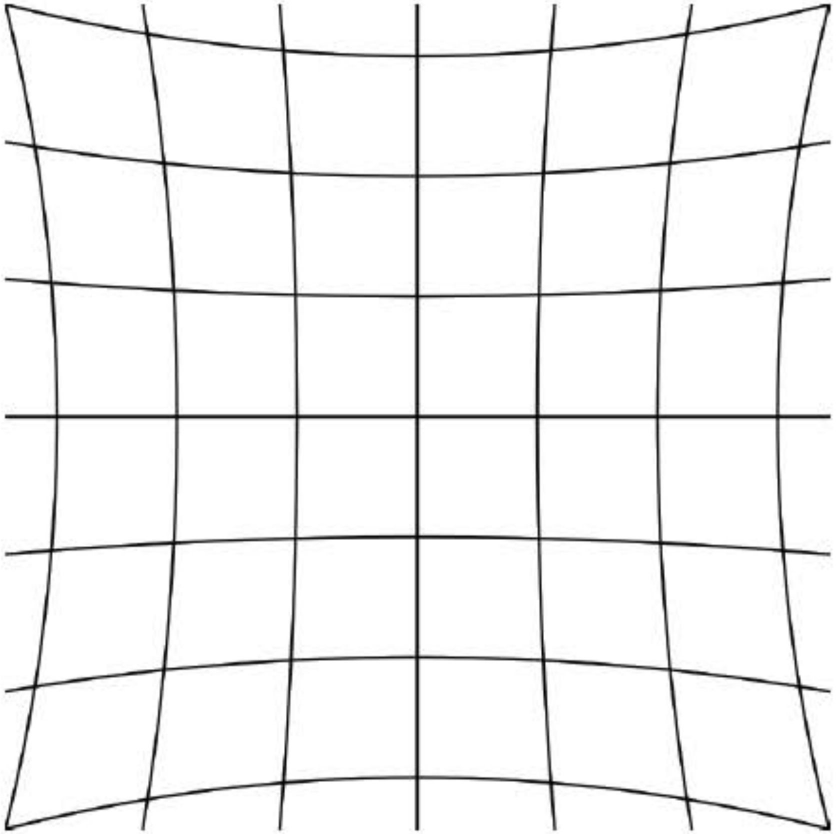
HTC Vive

To Correct for Distortion



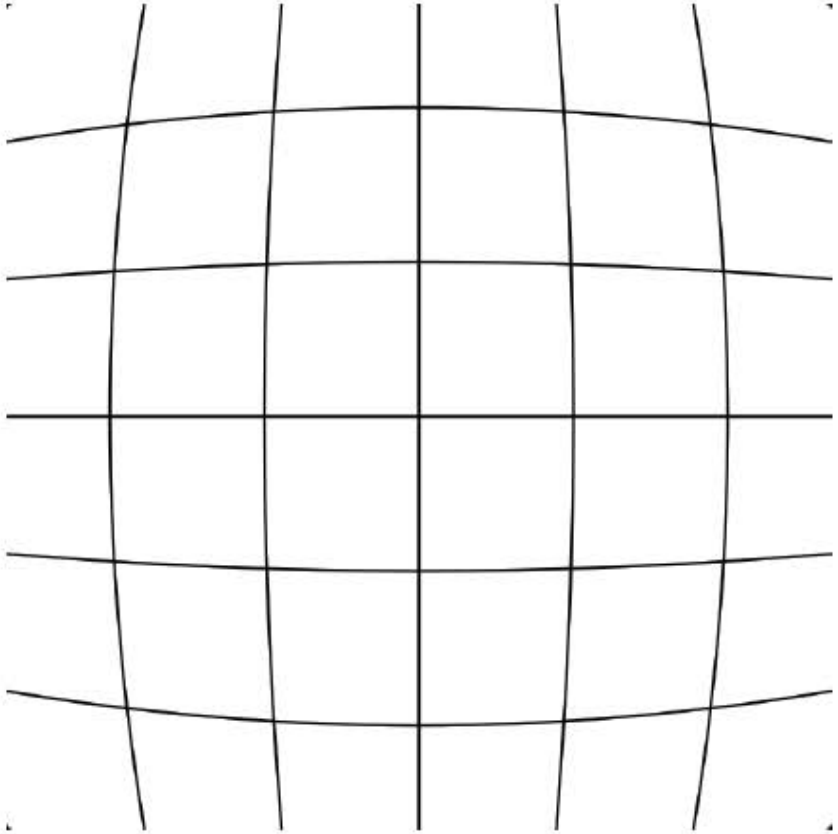
- Must pre-distort image
- This is a pixel-based distortion
- Graphics rendering uses linear interpolation!
- Too slow on most systems
- Use shader programming

Lens Distortion



Pincussion Distortion

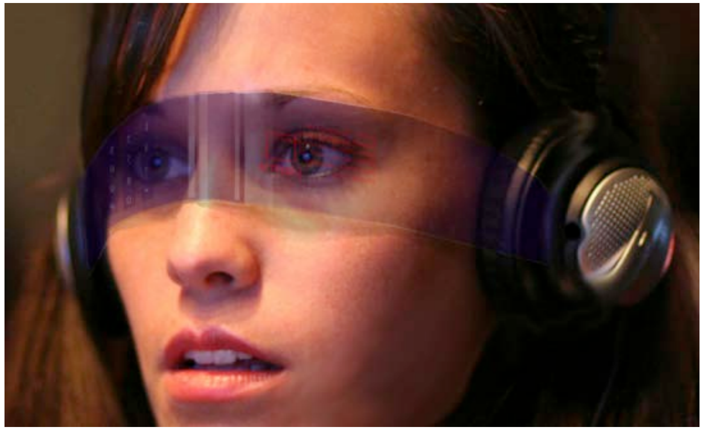
optical



Barrel Distortion

digital correction

HMD Design Trade-offs



vs.

- Resolution vs. field of view
  - As FOV increases, resolution decreases for fixed pixels
- Eye box vs. field of view
  - Larger eye box limits field of view
  - "eye box" ≈ space between eye and the device
- Size, Weight and Power vs. everything else

Oculus Rift

- Cost: $599 USD
- FOV: 110^{o} Horizontal
- Refresh rate: 90 Hz
- Resolution 1080x1200/eye
- 3 DOF orientation tracking
- 3 axis positional tracking

Inside an Oculus Rift

Oculus DK2 Teardown

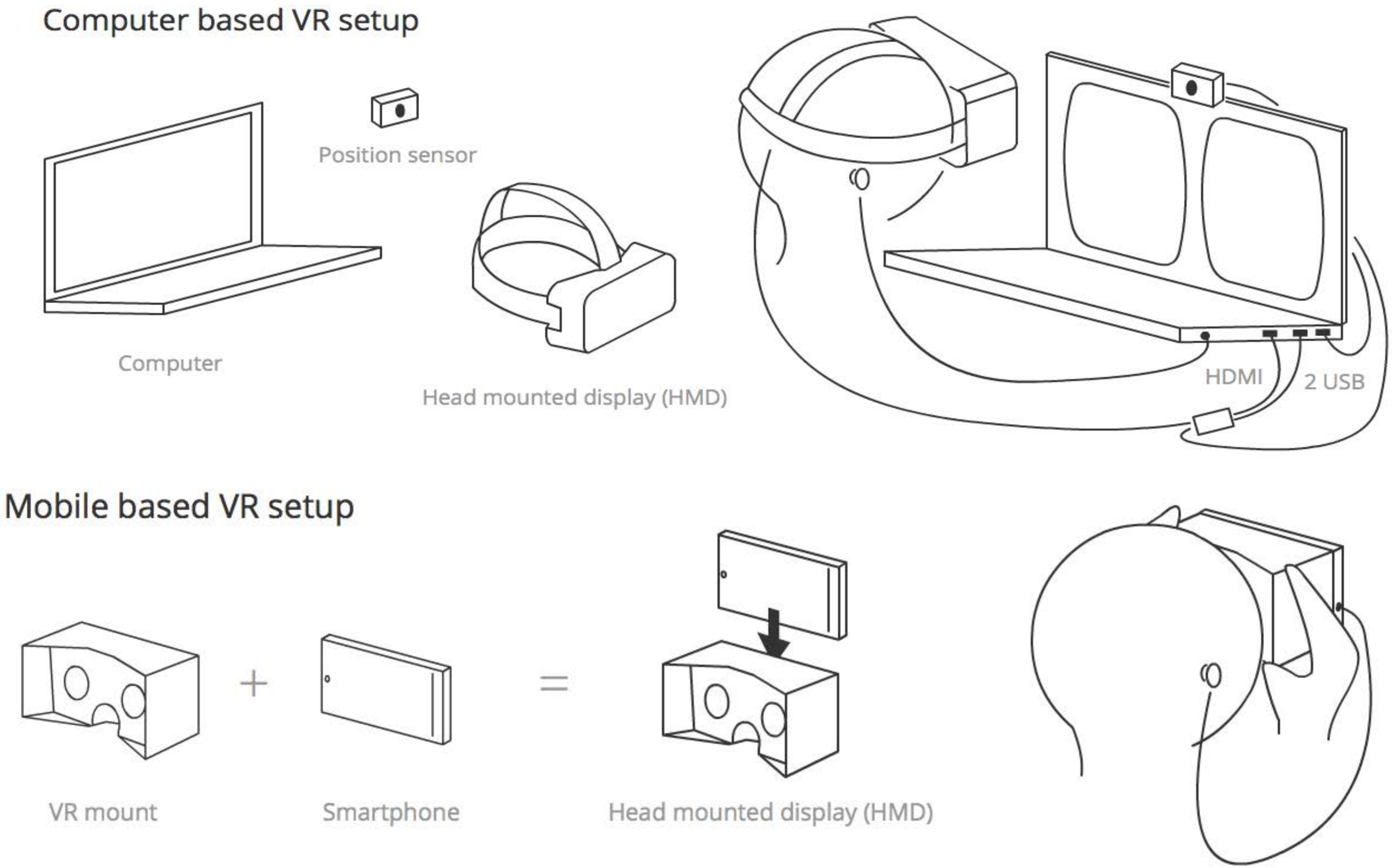
https://www.ifixit.com/Teardown/Oculus+Rift+Development+Kit+2+Teardown/27613

- Samsung 5.7” AMOLED: 1920x1080px, 75Hz
- 2 sets of lenses (for different prescriptions)
- InvenSense 6-axis IMU
- ARM Cortex-M3 MCU
- …

Comparison Between HMDs

					
Name	**Oculus Rift**	**HTC Vive**	**PlayStation VR**	**StarVR**	**OSVR HDK**
Manufacturer	Oculus VR	HTC, Valve	Sony	Starbreeze	Razer, Sensics
Display	2x OLED	2x OLED	OLED	2x LCD	LCD
Resolution	2160x1200px	2160x1200px	1920x1080px	5120x1440px	1920x1080px
Framerate	90fps	90fps	120fps	60fps	60fps
Field of view	>110°	>110°	100°	210°	100°
Positional tracking	6DOF	6DOF Valve Lighthouse	6DOF	6DOF	6DOF
Controller	Xbox One controller/Oculus Touch	two SteamVR controllers, one for each hand	Playstation Move/DualShock 4	-	-

Computer Based vs. Mobile VR Displays

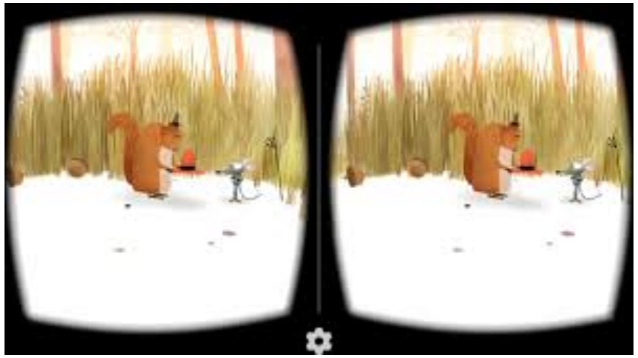



Google Cardboard

Google Cardboard

+

=



- Released 2014 (Google 20% project)
- >5 million shipped/given away
- Easy to use developer tools

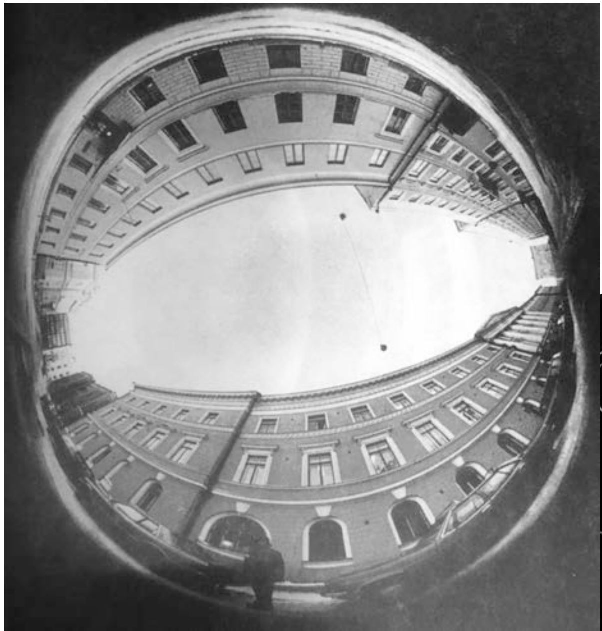
Multiple Mobile VR Viewers Available

Projection/Large Display Technologies

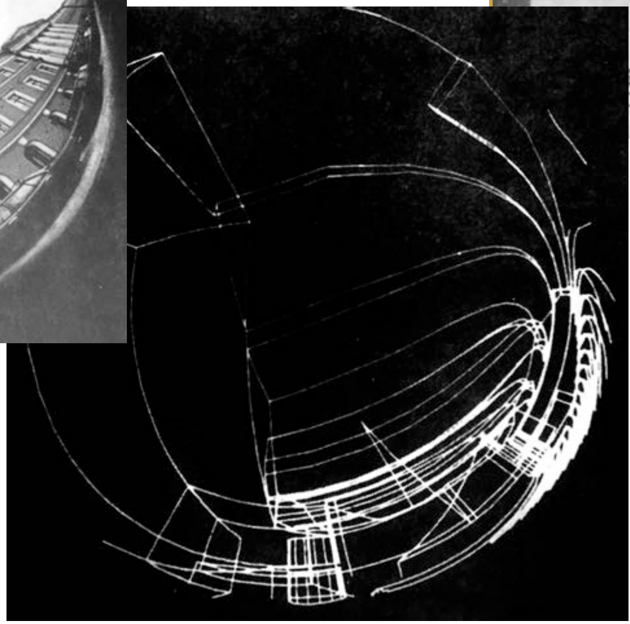
- Room Scale Projection
  - CAVE, multi-wall environment
- Dome projection
  - Hemisphere/spherical display
  - Head/body inside
- Vehicle Simulator
  - Simulated visual display in windows

A historical remark

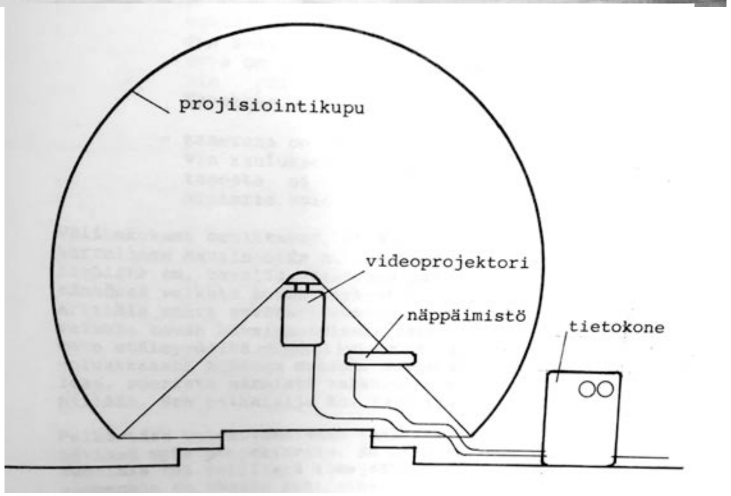
- Architectural visualization in a dome projection (1978)



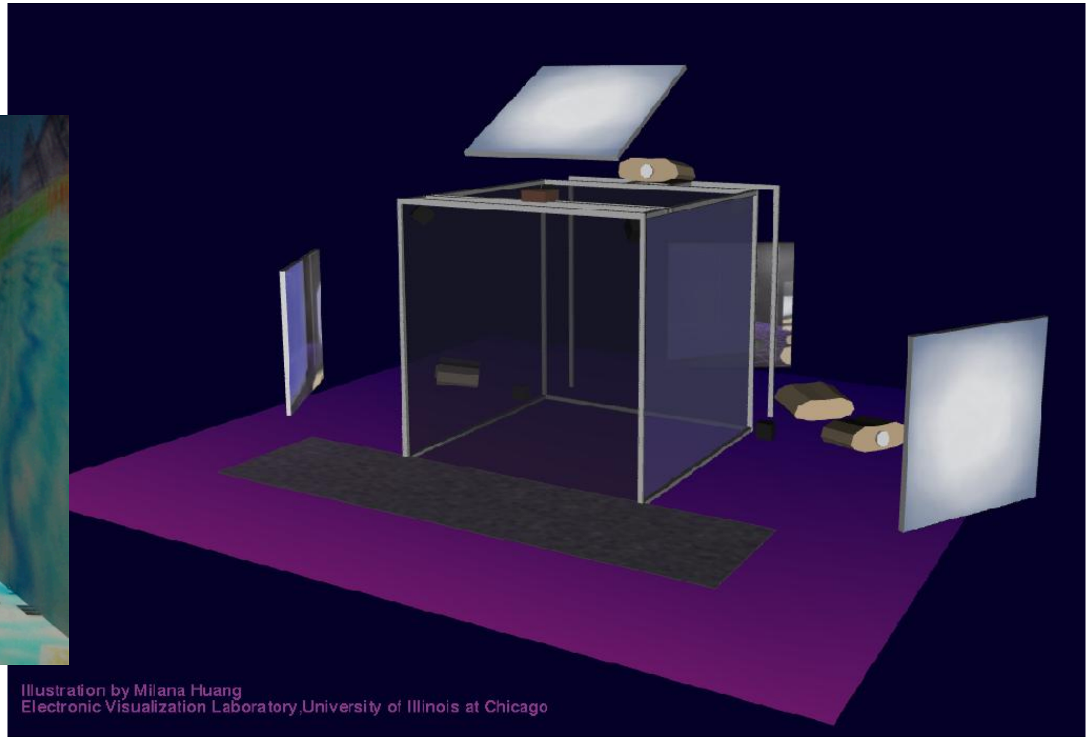
fisheye photo



computed projection
made by pen plotter



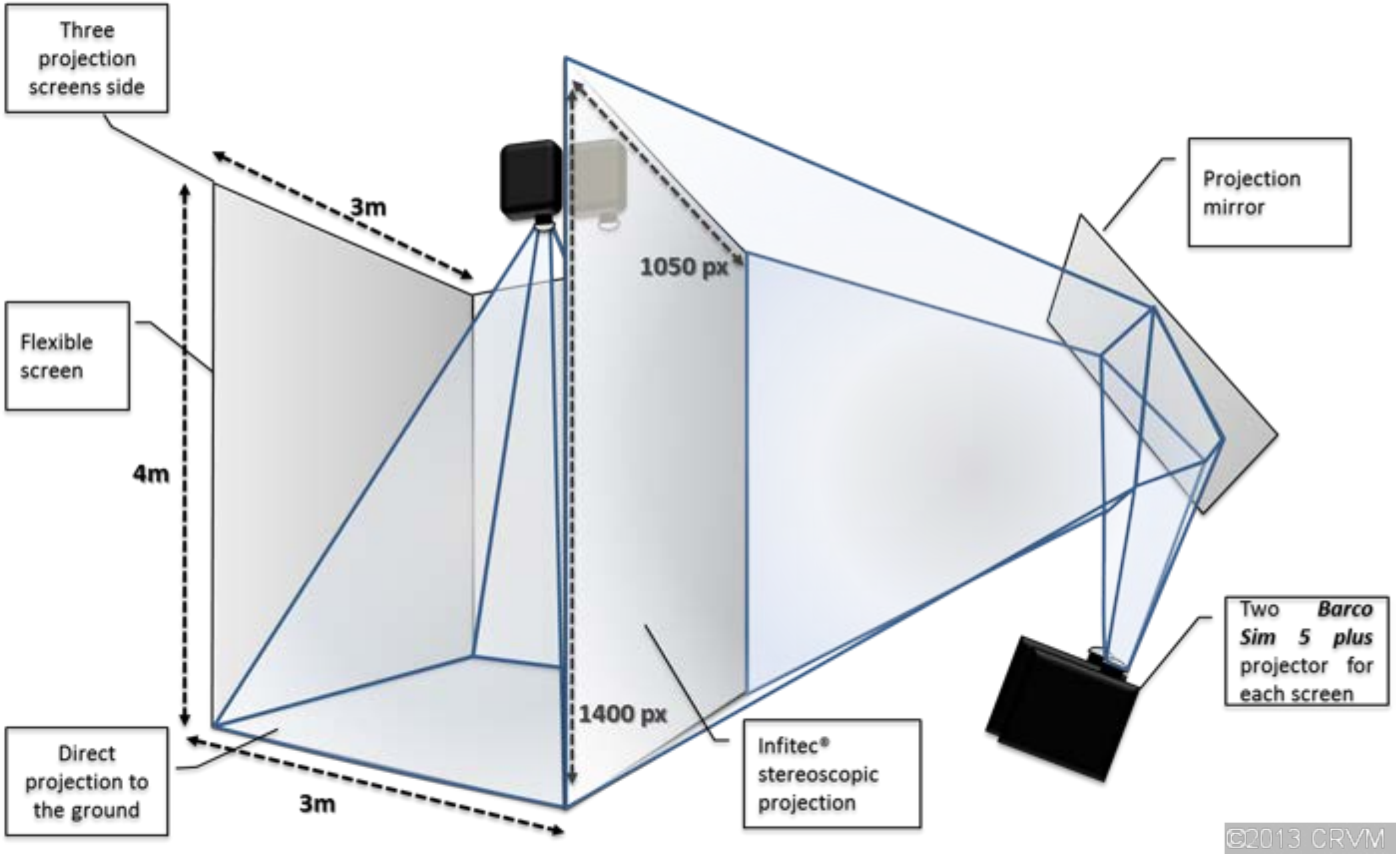
CAVE



- Developed in 1992, EVL University of Illinois Chicago
- Multi-walled stereo projection environment
  - Head tracked active stereo

Cruz-Neira, C., Sandin, D. J., DeFanti, T. A., Kenyon, R. V., & Hart, J. C. (1992). The CAVE: audio visual experience automatic virtual environment. *Communications of the ACM*, *35*(6), 64-73.

Typical CAVE Setup

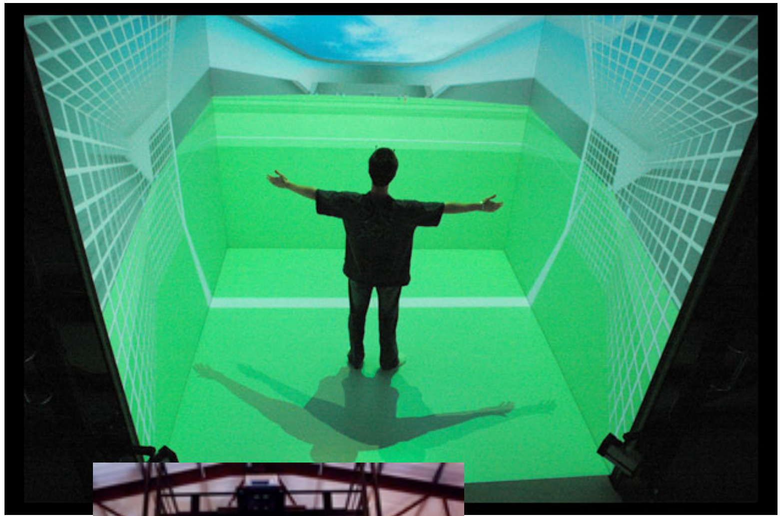


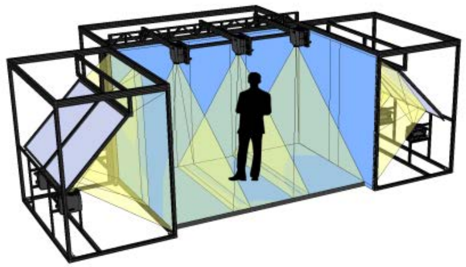
- 4 sides, rear projected stereo images

Demo Video – Wisconsin CAVE

- https://www.youtube.com/watch?v=mBs-OGDoPDY 1'40"

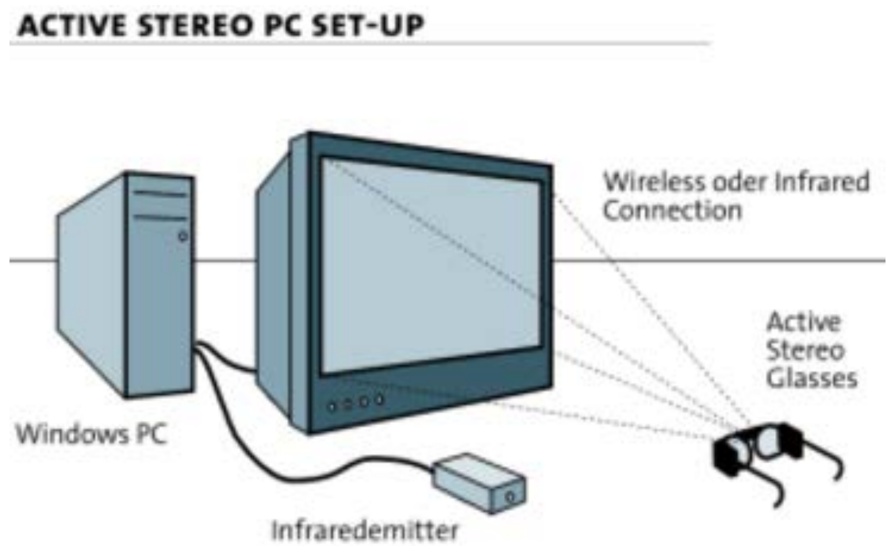
CAVE Variations

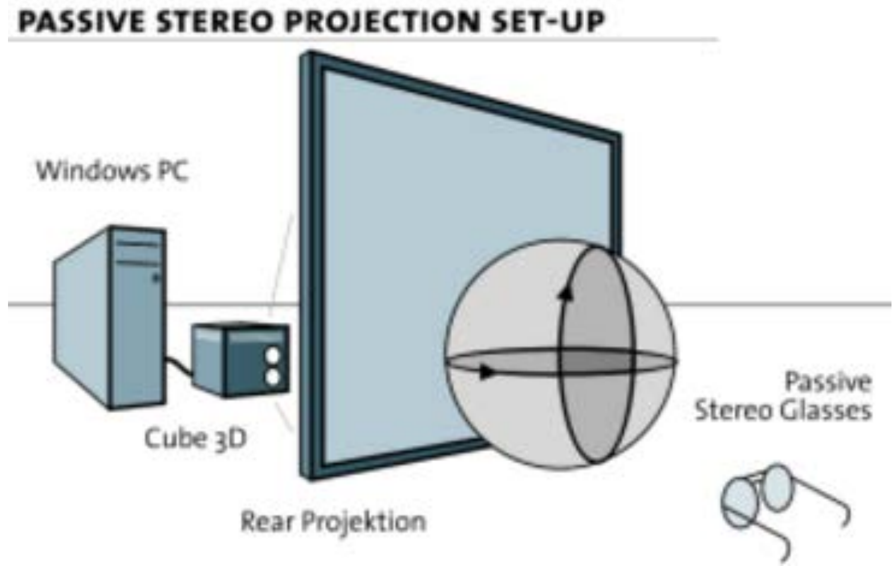




Stereo Projection

- Active Stereo
  - Active shutter glasses
  - Time synced signal
  - Brighter images
  - More expensive
- Passive Stereo
  - Polarized images
  - Two projectors (one/eye)
  - Cheap glasses (powerless)
  - Lower resolution/dimmer
  - Less expensive

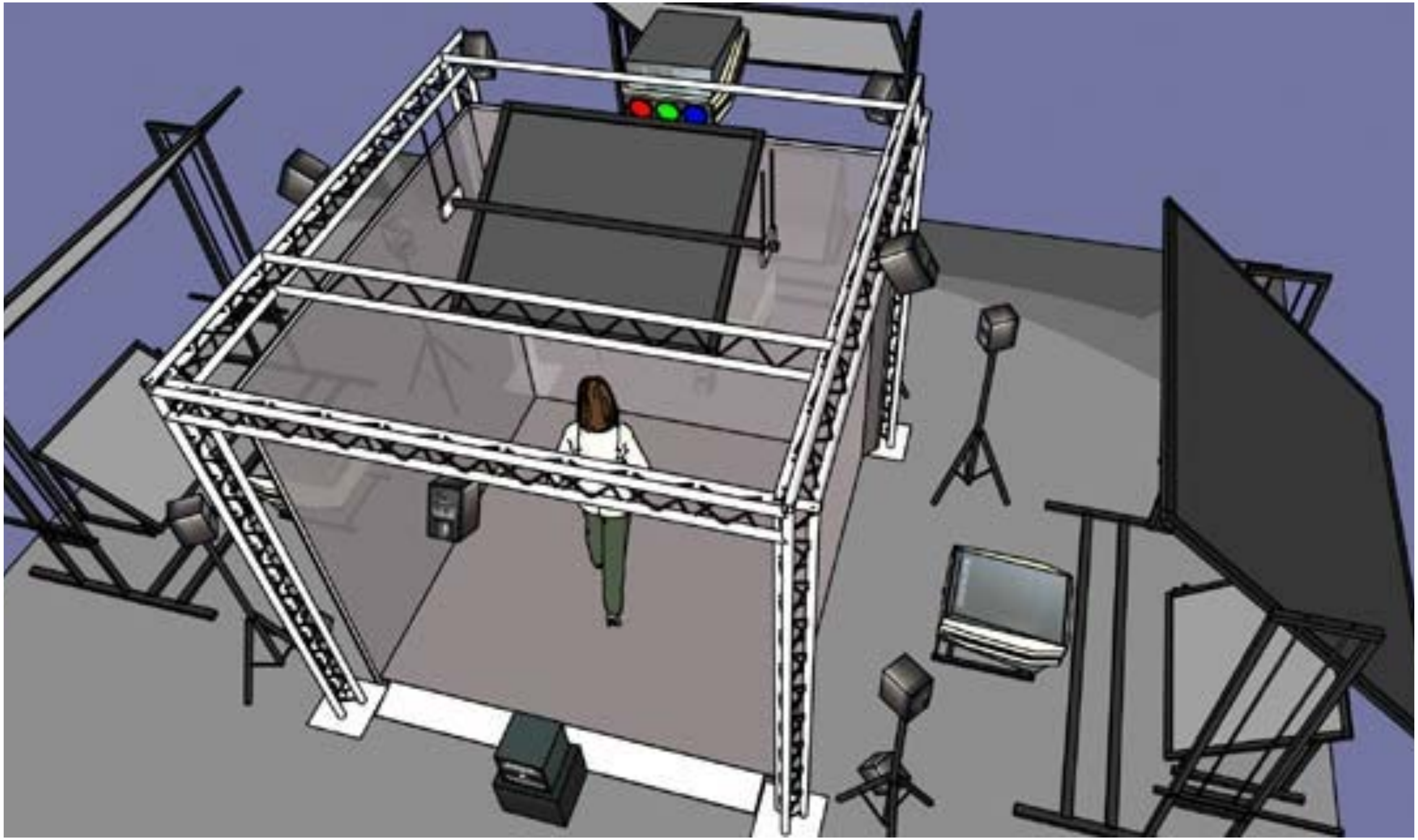




Caterpillar Demo

- https://www.youtube.com/watch?v=r9N1w8PmD1E 1'40"

EVE: Experimental Virtual Environment at Helsinki University of Technology (2000 - 2008)



http://eve.hut.fi

EVE Demos

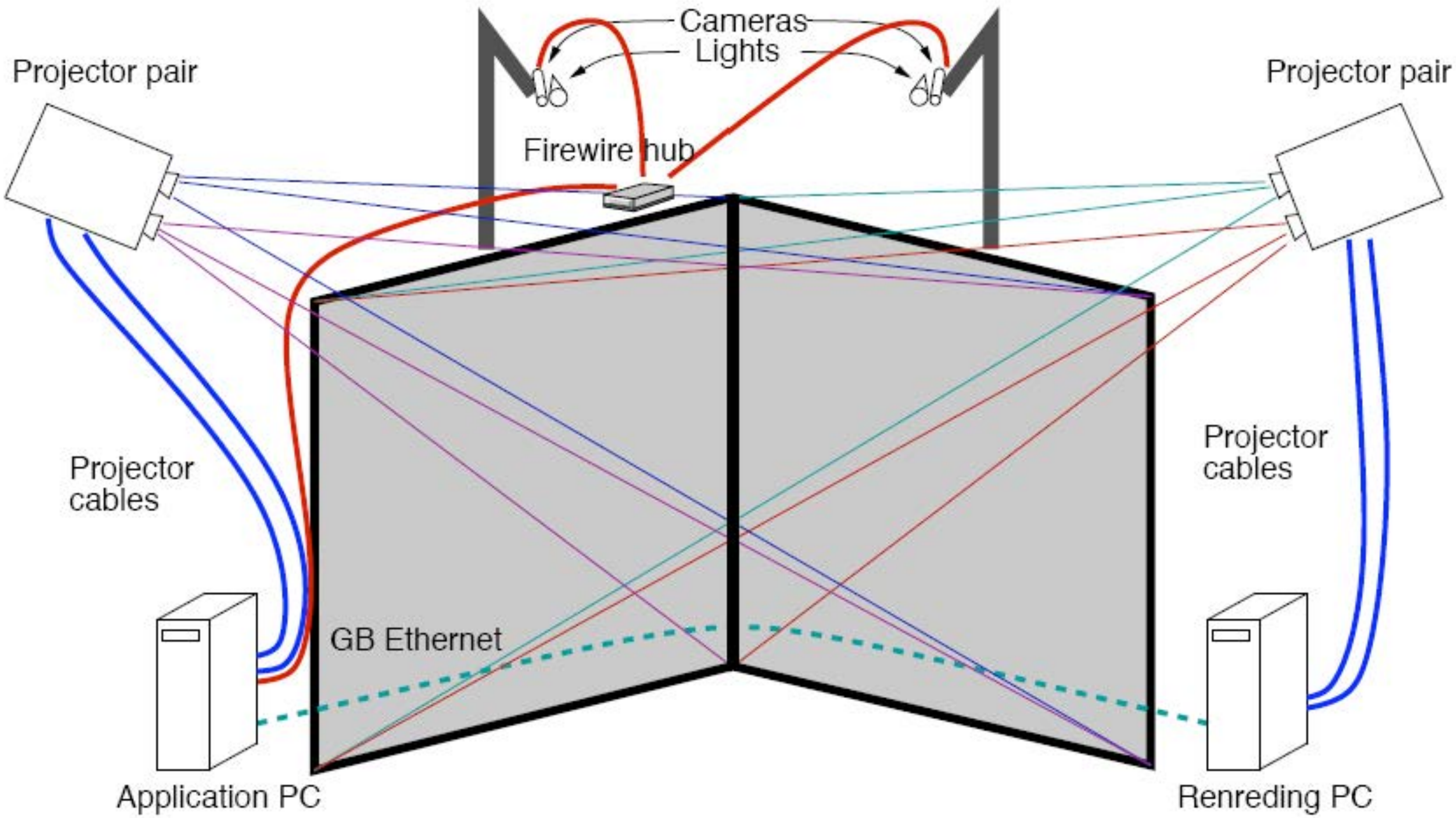
A virtual aquarium 1'08"

Architectural visualization 1'18"

Holma – Drawing in the air 3'43"

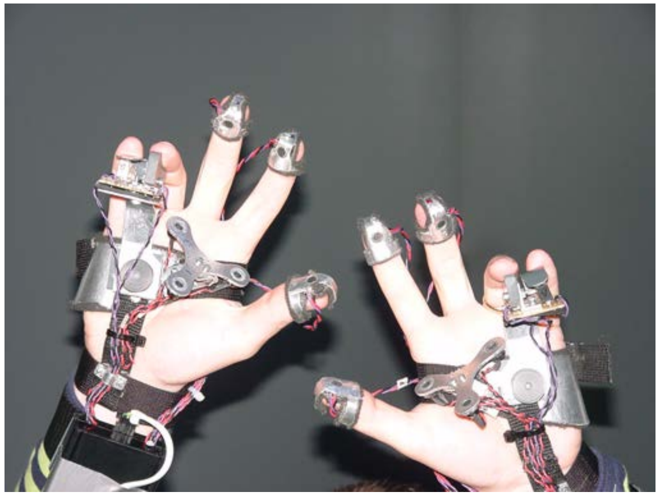
- http://eve.hut.fi
- choose tab 'Applications'

Upponurkka: a cheap two-wall cave



HELMA project: Drawing in the air

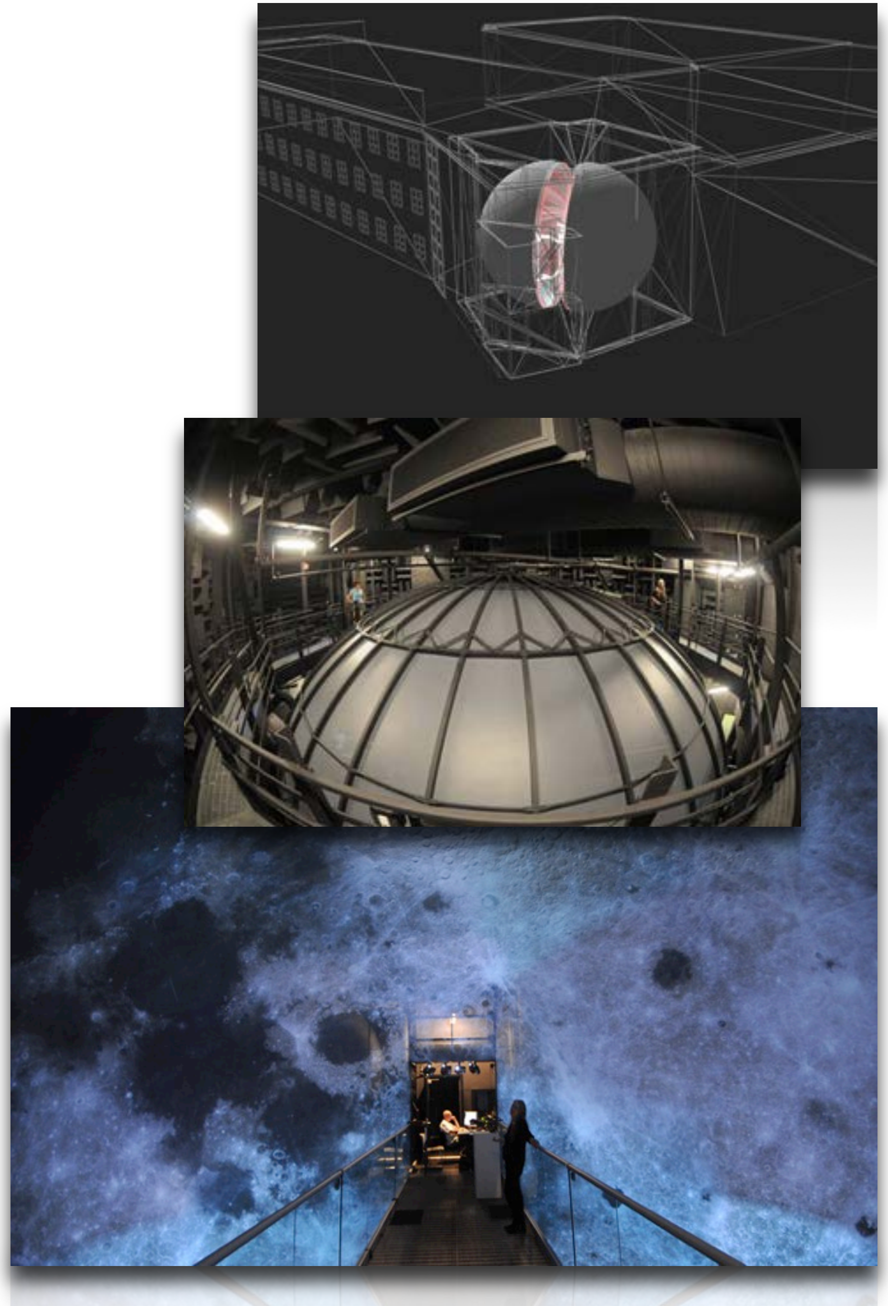
- Fine motor interaction methods for immersive free-hand expression
- a new art medium
- experiments with artists
  - exhibition at the Kiasma museum (2005)



Allosphere

- Univ. California Santa Barbara
  - One of a kind facility
- Immersive Spherical display
  - 10 m diameter
  - Inside 3 story anechoic cube
  - Passive stereoscopic projection
  - 26 projectors
  - Visual tracking system for input
- See http://www.allosphere.ucsb.edu/

Kuchera-Morin, J., Wright, M., Wakefield, G., Roberts, C., Adderton, D., Sajadi, B., ... & Majumder, A. (2014). Immersive full-surround multi-user system design. *Computers & Graphics*, *40*, 10-21.



Allosphere Demo

- https://www.youtube.com/watch?v=25Ch8eE0vJg

1'40"

Vehicle Simulators

- Combine VR displays with vehicle
  - Visual displays on windows
  - Motion base for haptic feedback
  - Audio feedback
- Physical vehicle controls
  - Steering wheel, flight stick, etc
- Full vehicle simulation
  - Emergencies, normal operation, etc
  - Weapon operation
  - Training scenarios

Demo: Boeing 787 Simulator

- https://www.youtube.com/watch?v=3iah-blsw_U

1'40"