Virtual Reality and Multi-Sensory Interaction

Master Research in Computer Science (SIF)

Ferran Argelaguet

ferran.argelaguet@inria.fr

About Myself

➢ Inria Research Scientist (France)

- Habilitation in computer science 2021 (Univ. Rennes 1, France)
- PhD in computer science 2011 (UPC, Spain)

➢ Member of the Inria's Hybrid team

- Virtual and Augmented Reality
- @Hybrid_TeamVR
- https://team.inria.fr/hybrid

Research @Hybrid

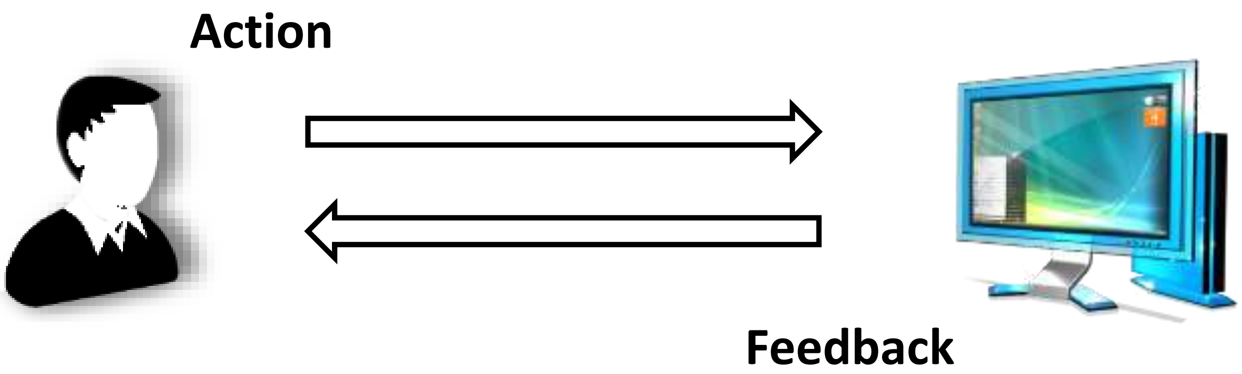
Contents

- Introduction
  - Definitions
  - A short history of user interfaces
- The User in the Loop
  - Human perception
    - Distance perception
    - Motion perception
    - Avatar perception
  - Human performance models
- Interaction techniques
  - Input Devices
  - Interaction Tasks: Selection, Manipulation, Navigation, Application Control

Definitions

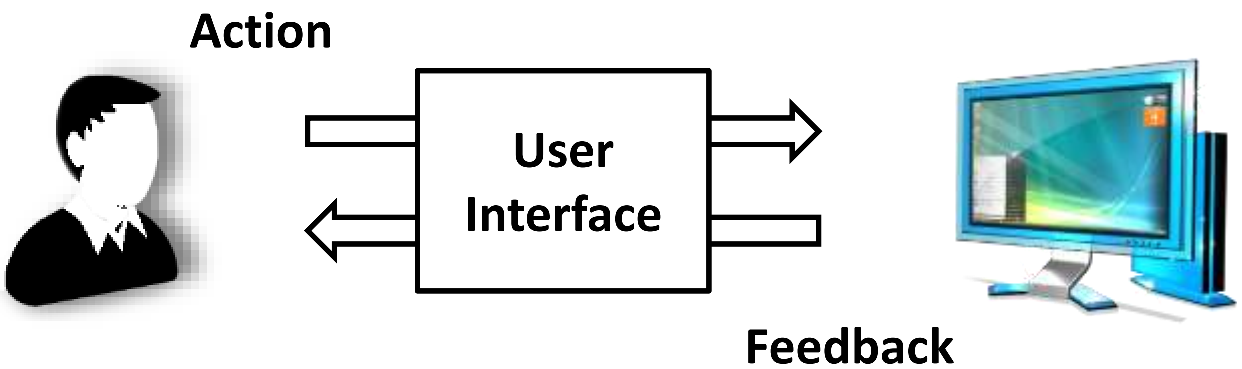
Human-Computer Interaction (HCI)

- Communication process between users and computers
- Design, implementation and evaluation of interactive systems.



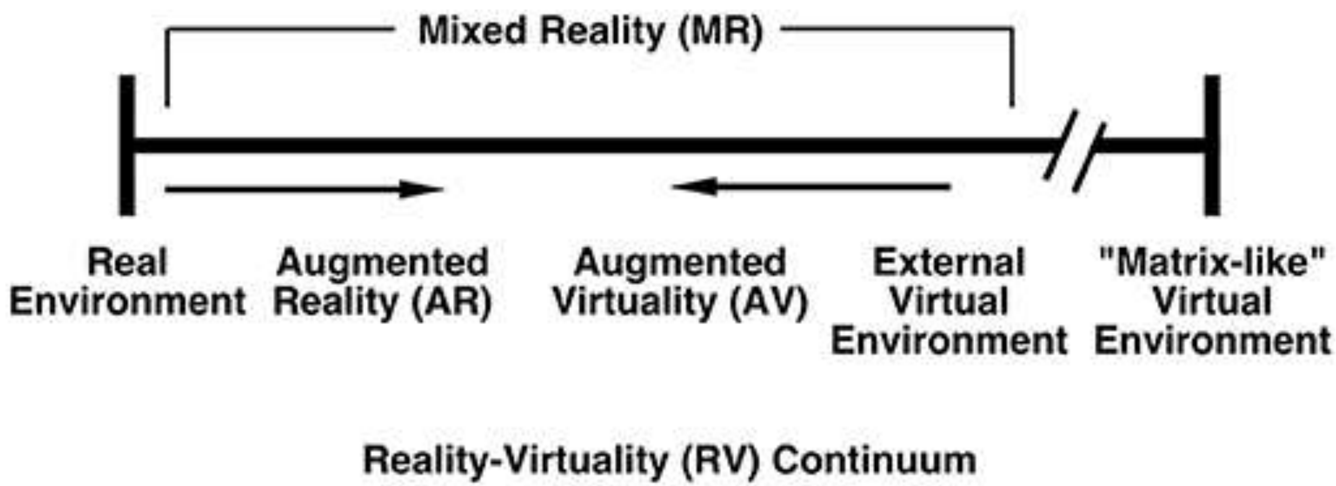
User Interface

- Medium through which the communication takes place
  - Translates user actions (inputs) and computer states (outputs)
  - A good UI should balance expressiveness and simplicity



Other Realities – Milgram's Continuum

- Reality-Virtuality continuum
  - Introduced by Paul Milgram and Fumio Kishino in 1994
- Merging of real and virtual environments
  - Physical an digital objects co-exist and interact in real time
  - Mixed reality is the spectrum between real and purely virtual environments

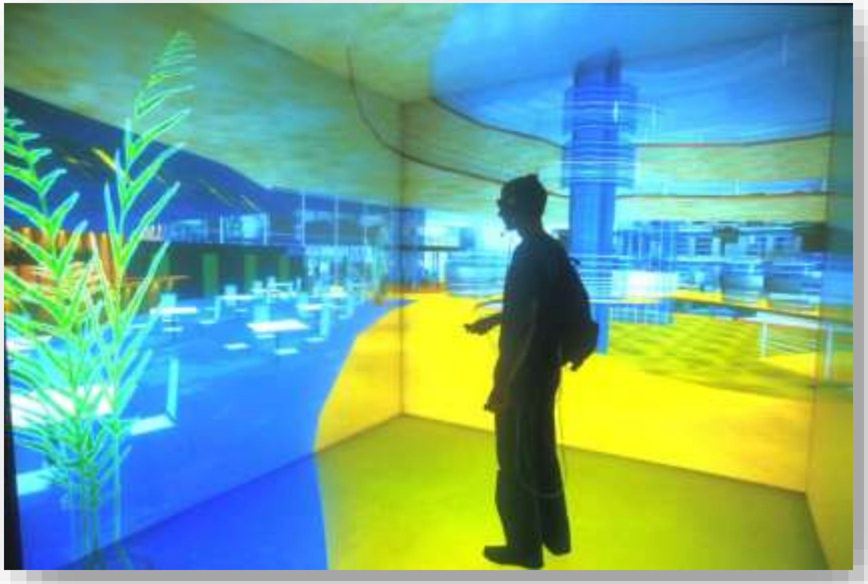


Skarbez R, Smith M and Whitton MC (2021) Revisiting Milgram and Kishino's Reality-Virtuality Continuum. *Front. Virtual Real.* 2:647997. doi: 10.3389/frvir.2021.647997

Virtual Reality

*"Virtual reality is a scientific domain that use **computer science** and **interaction interfaces** in order to simulate, in a virtual world, the behaviour of 3D entities that are interacting in **real time** with themselves and with one or more users. The user's sensorymotor channels are engaged in a pseudo-natural immersion"*

Traité de la réalité virtuelle



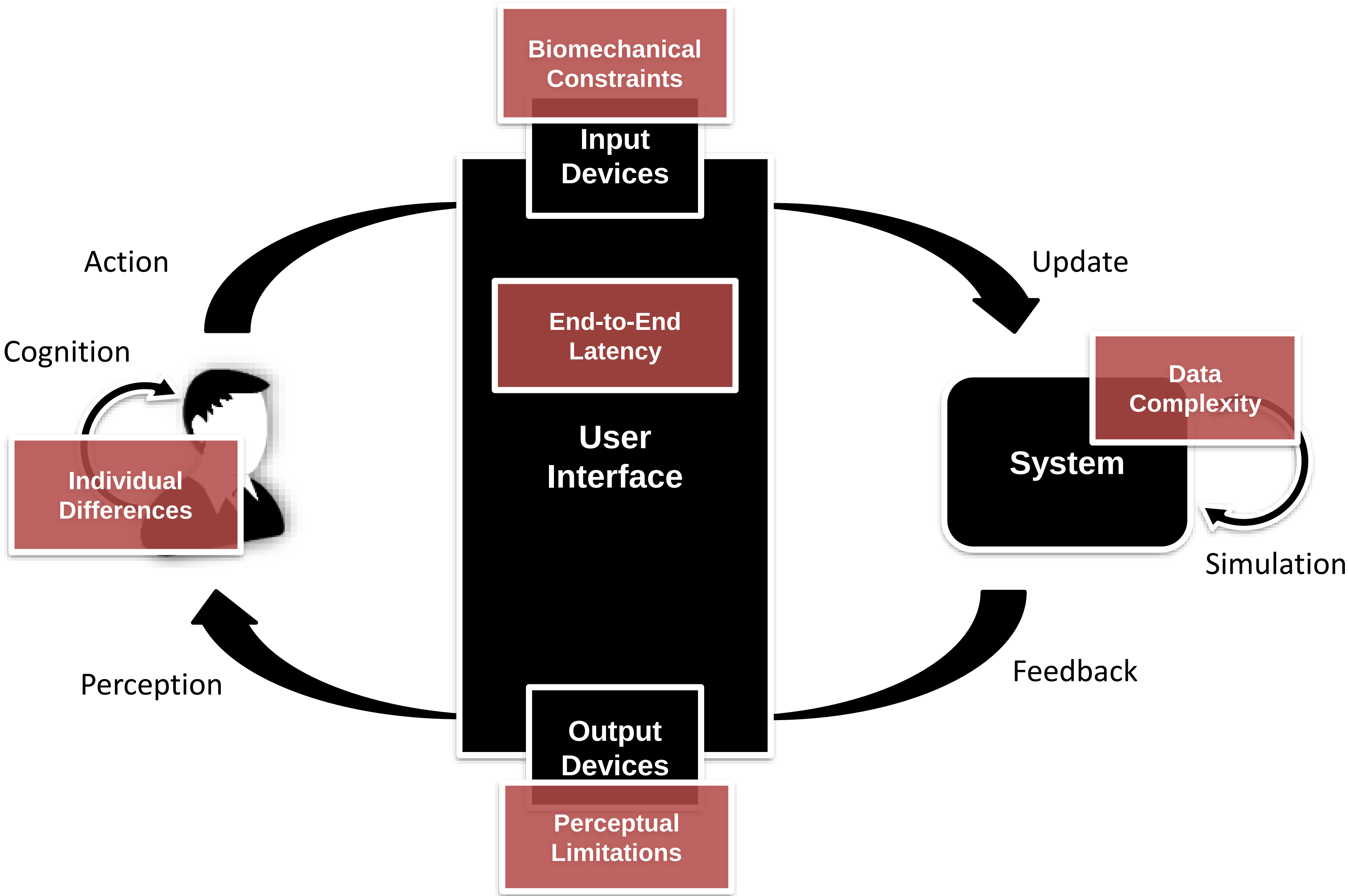
Augmented Reality

- Computer generated information are added to the perception of a real scene
- Main goal
  - Support the user in real world tasks
  - Increase user's performance
  - Augment user's perception

Hyper-Reality, Keiichi Matsuda

Ikea

The Interaction Loop



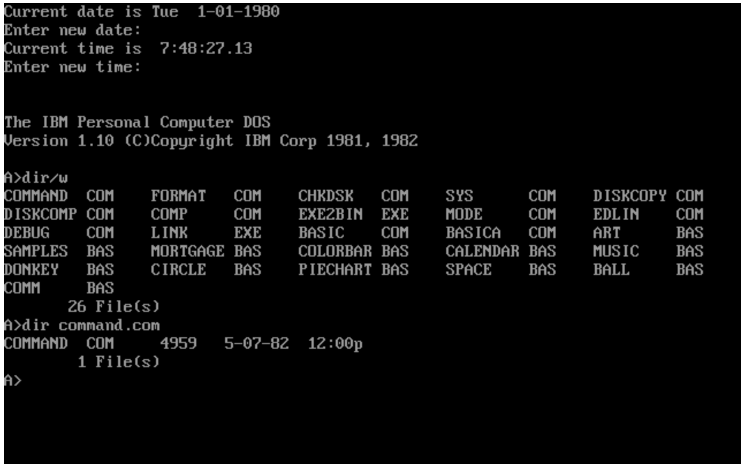
A Short History of User Interfaces

User Interface in Real Life

PHOTO: NPH / DIETER MATHIS/PICTURE-ALLIANCE/DPA/AP IMAGES

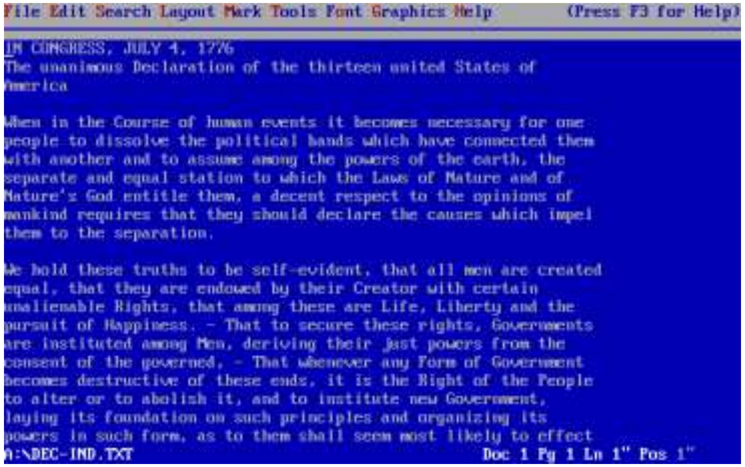
Command-line User Interface

1981



https://en.wikipedia.org/wiki/IBM_PC_DOS#/media/File:PC_DOS_1.10_screenshot.png

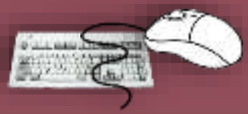
https://commons.wikimedia.org/wiki/File:MS-DOS_install_welcome.gif



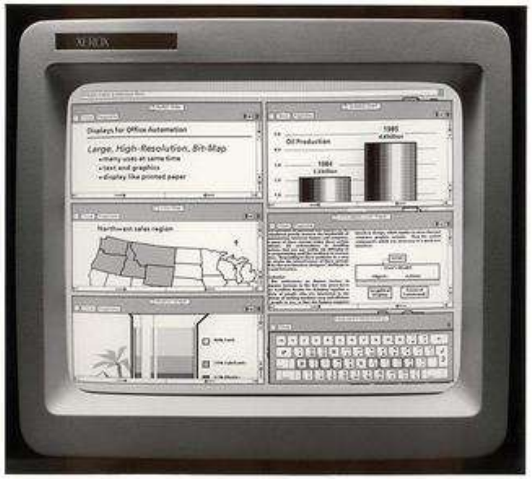
https://commons.wikimedia.org/wiki/File:Wordperfect-5.1-dos.png

https://en.wikipedia.org/wiki/Norton_Commander#/media/File:Norton_Commander_5.51.png

Graphical User Interfaces

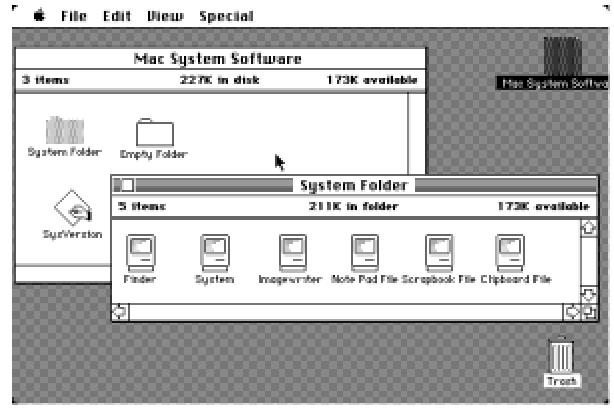


1973



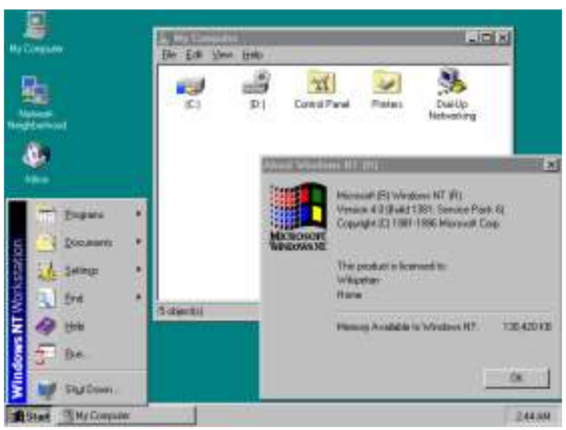
https://upload.wikimedia.org/wikipedia/en/1/1d/Xerox_Star_8010_workstations.jpg

1984

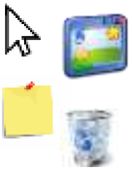


https://en.wikipedia.org/wiki/File:Apple_Macintosh_Desktop.png

1996



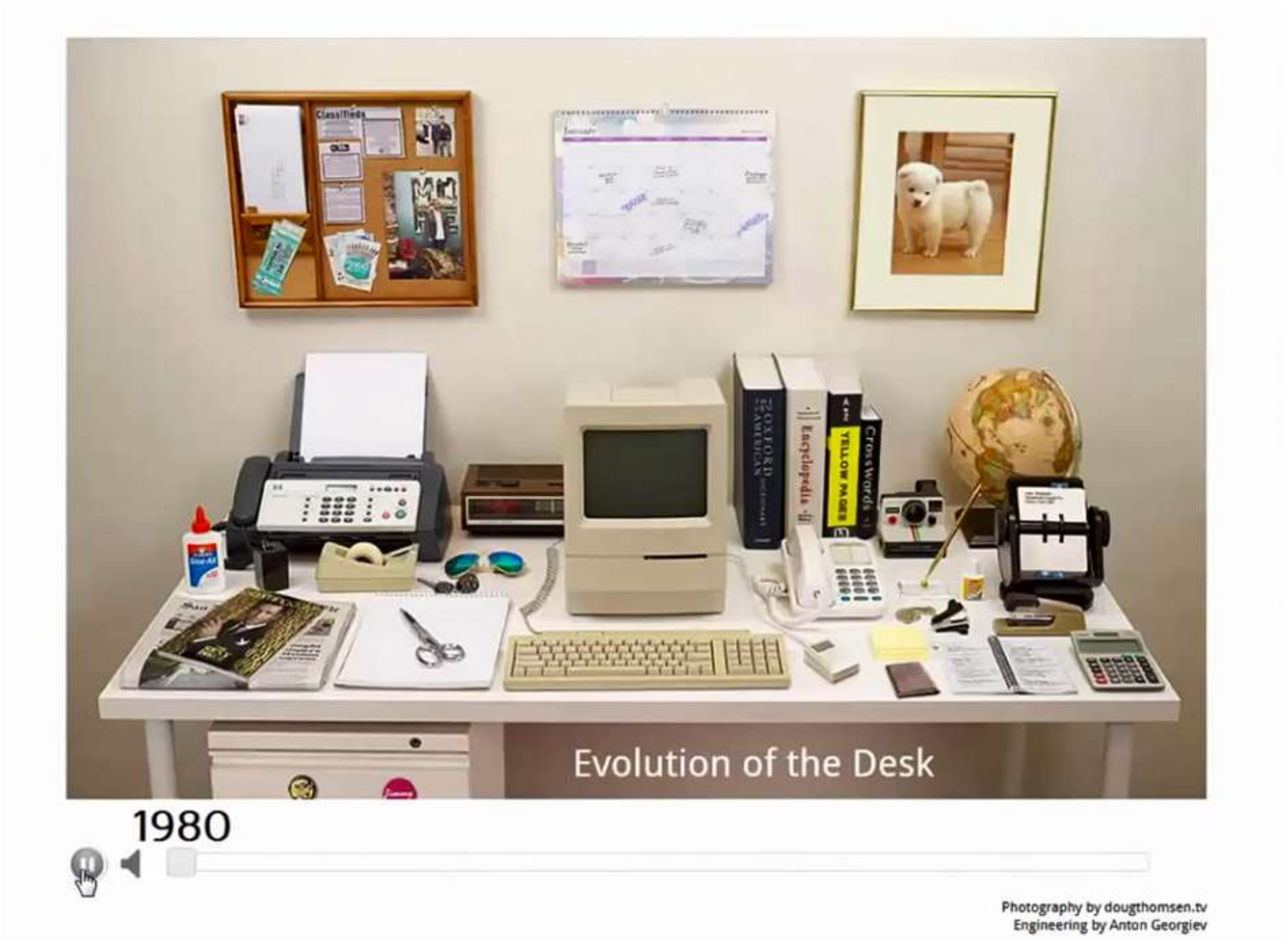
https://en.wikipedia.org/wiki/File:Windows_NT_4.0.png



2001

https://en.wikipedia.org/wiki/Mac_OS_X_10.0

The desktop

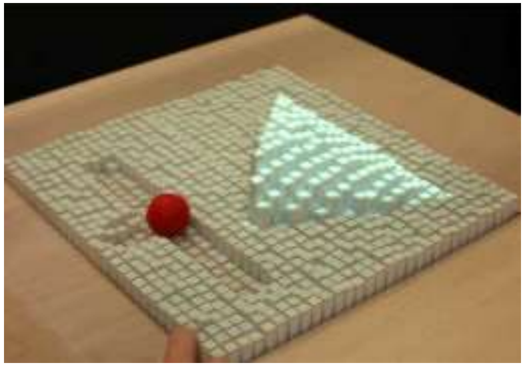


https://www.youtube.com/watch?v=uGI00HV7Cfw

Post-WIMP User Interfaces

- Direct and tangible interfaces

S. Jordà, et al. 2007. The reacTable: exploring the synergy between live music performance and tabletop tangible interfaces. ACM *International conference on Tangible and embedded interaction*

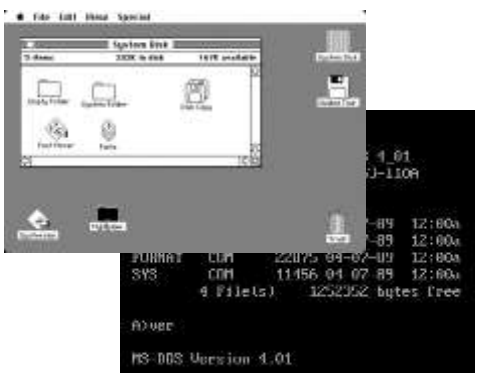


Follmer, Sean, et al. "inFORM: dynamic physical affordances and constraints through shape and object actuation." *Uist*. Vol. 13. 2013.

S. Pick, B. Weyers, B. Hentschel and T. W. Kuhlen, "Design and Evaluation of Data Annotation Workflows for CAVE-like Virtual Environments," in *IEEE Transactions on Visualization and Computer Graphics*, vol. 22, no. 4, pp. 1452-1461, 2016.

Trends in UI Evolution

- Increased functionality and data management
- User customization and Interface adaptation
- Natural user interfaces and multimodal feedback
- Immersion (increased display size, VR, AR)
- Multi-user collaboration



The origins of Virtual Reality

- 1962: Sensorama (Morton Heilig)
  - Earliest known examples of immersive, multi-sensory system
- 1965: The Ultimate Display (Ivan Sutherland)
  - Data visualization: “A display connected to a digital computer …is a looking glass into a mathematical wonderland.”
  - Sensors: “The computer can easily sense the positions of almost any of our body muscles.”
  - Virtual Environment: “The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in.”
- 1968: A Head-Mounted Three Dimensional Display
  - AFIPS Conference Proceedings, Vol. 33, Part I, 1968, pp. 757-764

Long process

Foundations → Technological Development → First Applications → Industrial Maturity → General Public

1960 1980 1990 2000 2010 2020

Sensorama 1962

HMD Nasa, 1984

Surgical Planning,
S. Cotin 1996

Force Feedback
PSA, 2005

Oculus/Meta

Industrial interest for VR / AR

- To do things better
  - Time-saver
    - Design
    - Prototyping
    - Training
  - Project review
    - Limit the use of the physical mock-up
    - Access to digital mock-up
    - Multi-users / multi-competencies
  - To be free
    - Of the equipment availability
    - Of the dangerousness of the equipment for the user

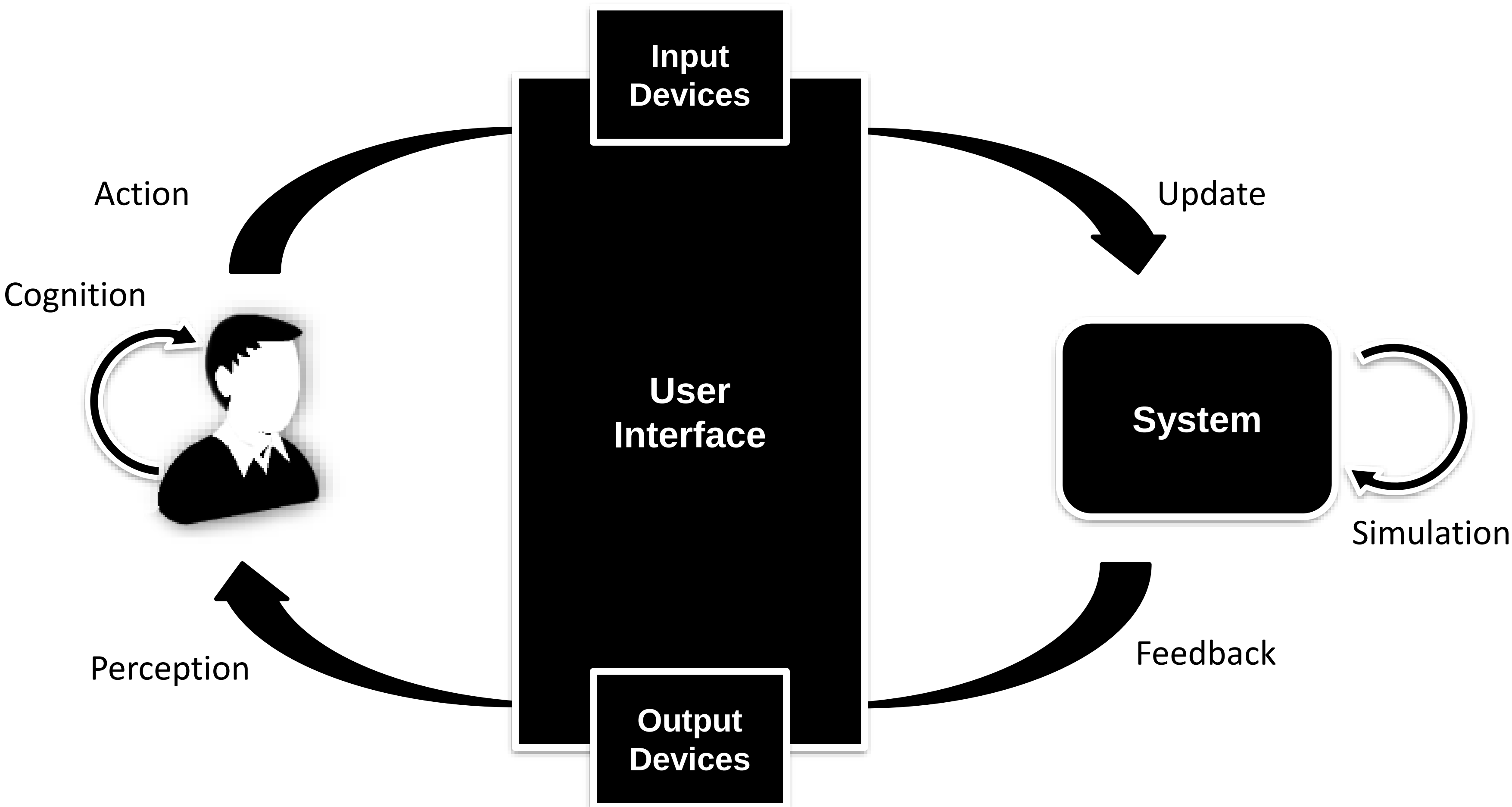
- To make differently, to invent
  - Access to time and/or space scale and virtual sensors
    - Relativistic physics
    - Geological applications
    - Multiscale Data
  - Access to hidden data
    - Scientific Visualization
    - Ex: constraints inside a 3D object
  - New functionality
    - New metaphors to explore data
    - Multimodality: Haptics / Sound / Vision

3D User Interfaces

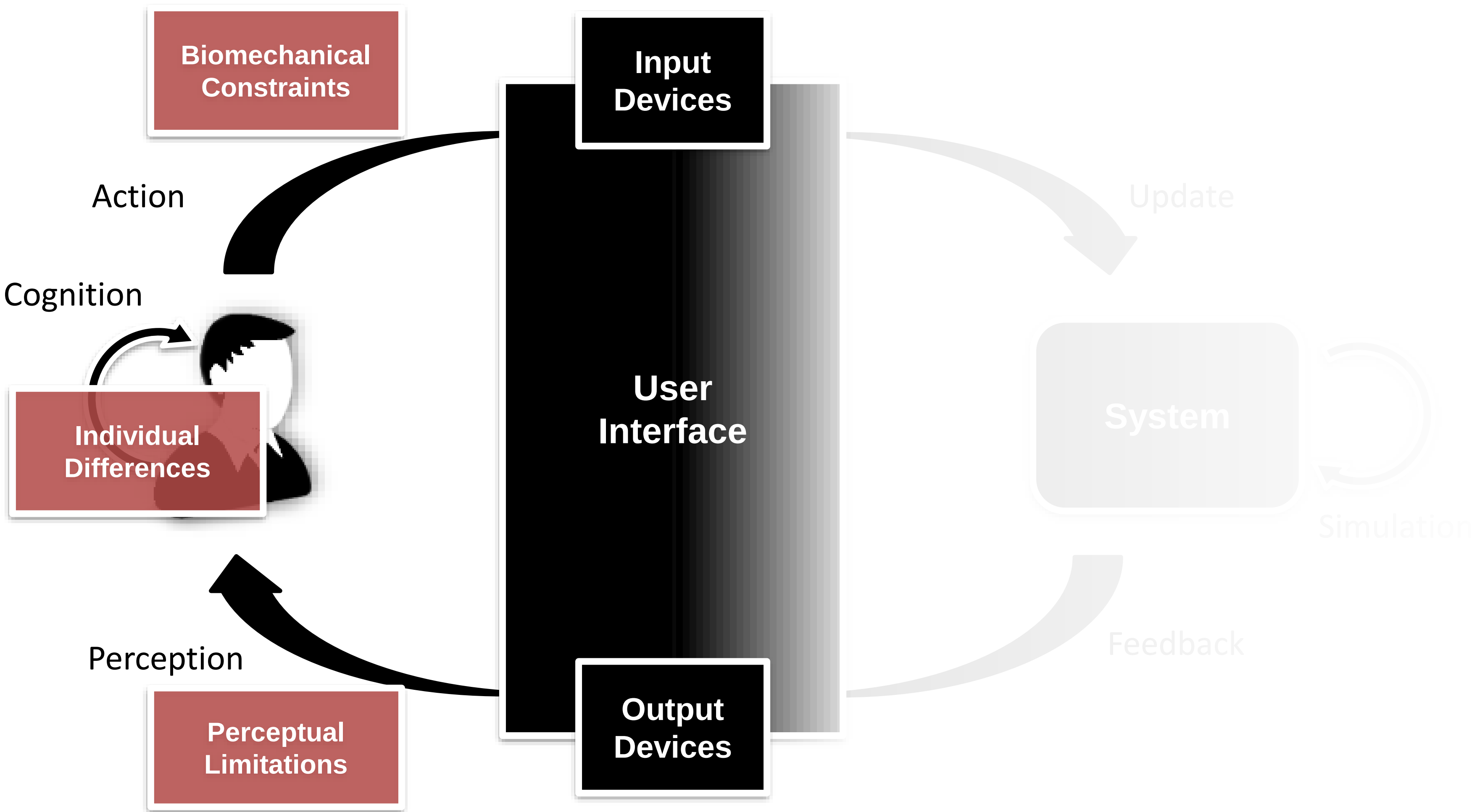
Siggraph 2017 – Unity VR Editor
https://www.youtube.com/watch?v=DkMfBIn81Xk

The User in the Loop

The Interaction Loop



The Interaction Loop

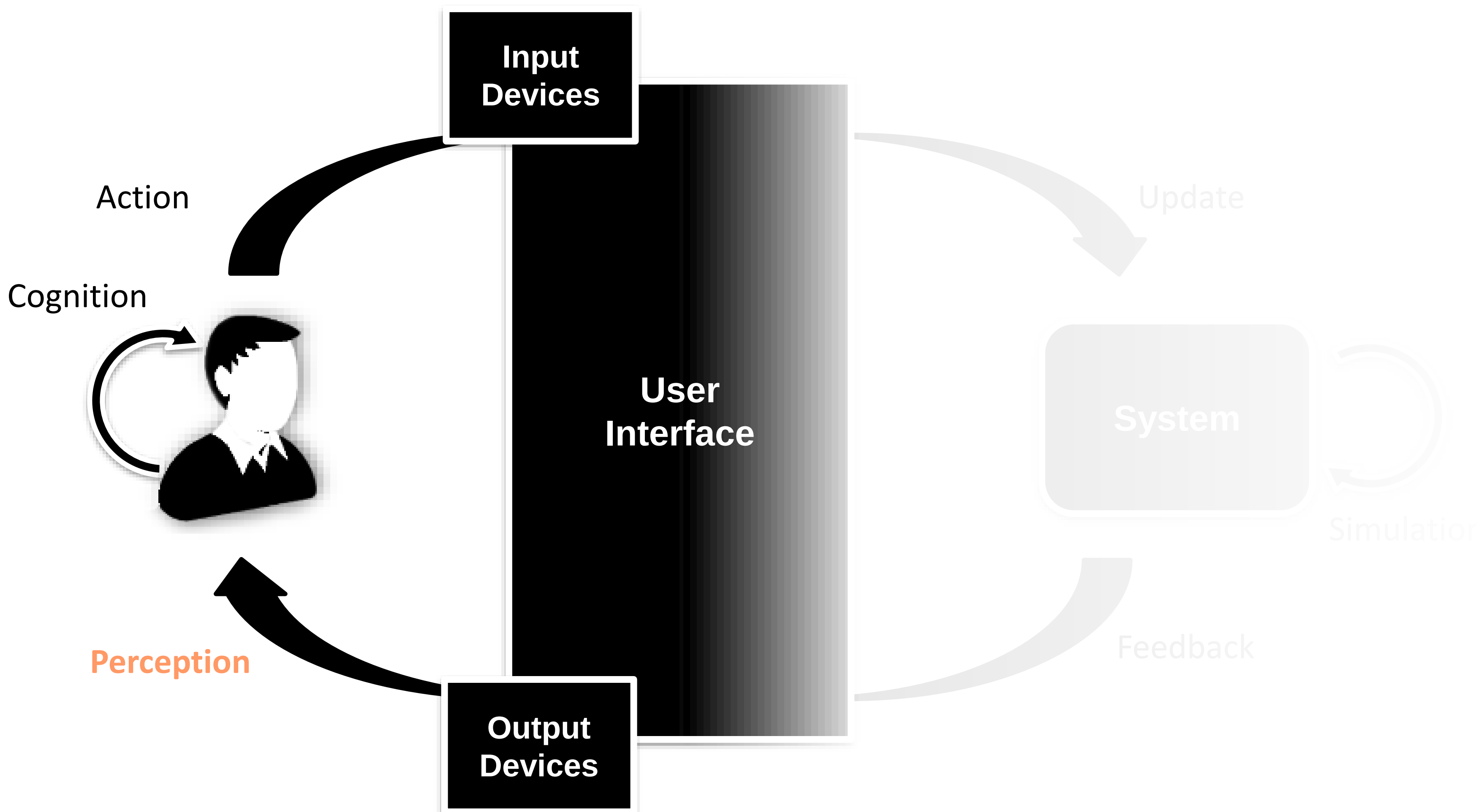


Human Perception

Towards the Holodeck

Star Trek

The Interaction Loop



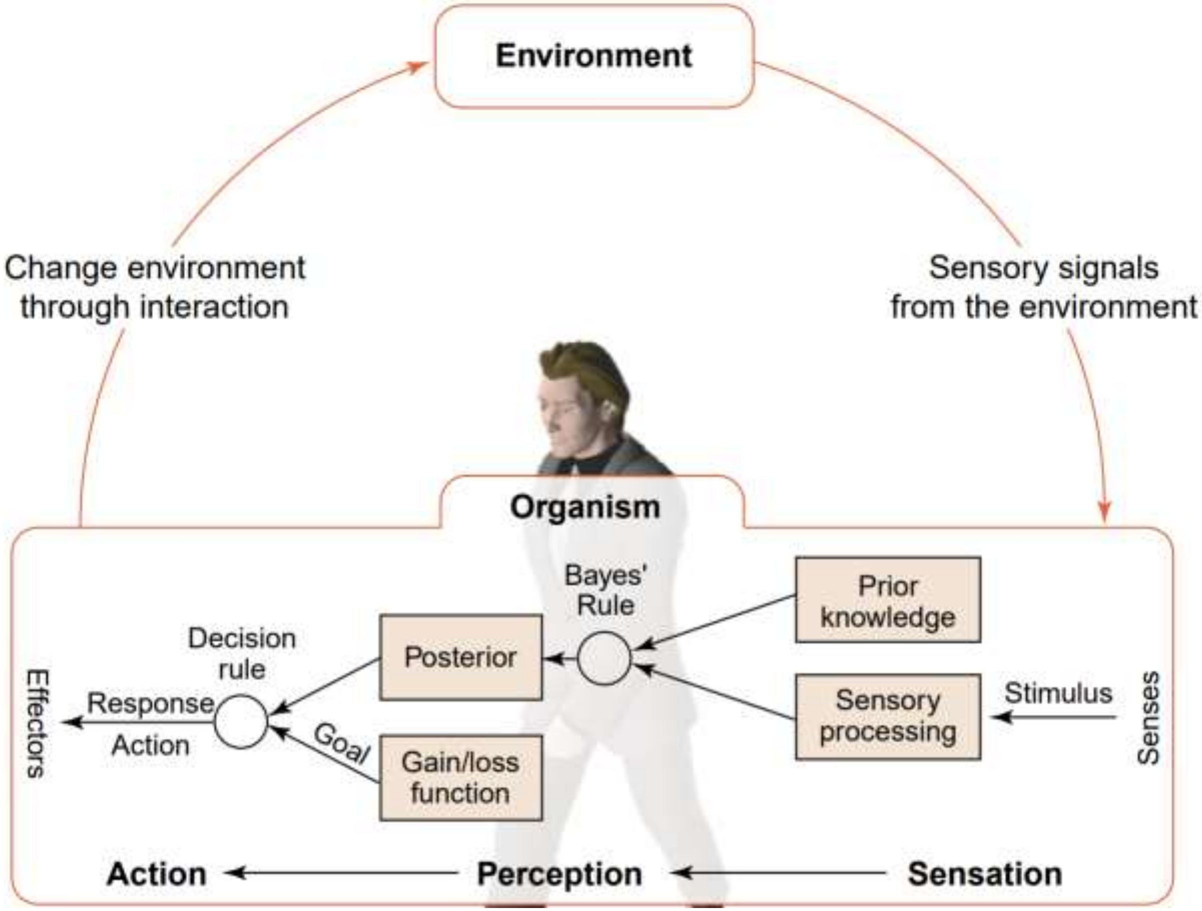
Human Perception

- The process by which sensory information is actively organized and interpreted by the brain.
  - Bottom-up: analysis of information incoming from sense receptors
  - Top-down: drawing meanings from experience and expectations

- The combination of the different sensory modalities allows humans to build a percept of their reality
  - Visual, Haptic, Acoustic, Olfactory, Taste

- Covered topics
  - Distance perception
  - Motion perception
  - Haptic perception (later in the course)

Bayesian framework



The perception–action loop, incorporating a Bayesian framework.

Marc O. Ernst, Heinrich H. Bülthoff, Merging the senses into a robust percept, Trends in Cognitive Sciences, Volume 8, Issue 4, 2004, Pages 162-169, ISSN 1364-6613

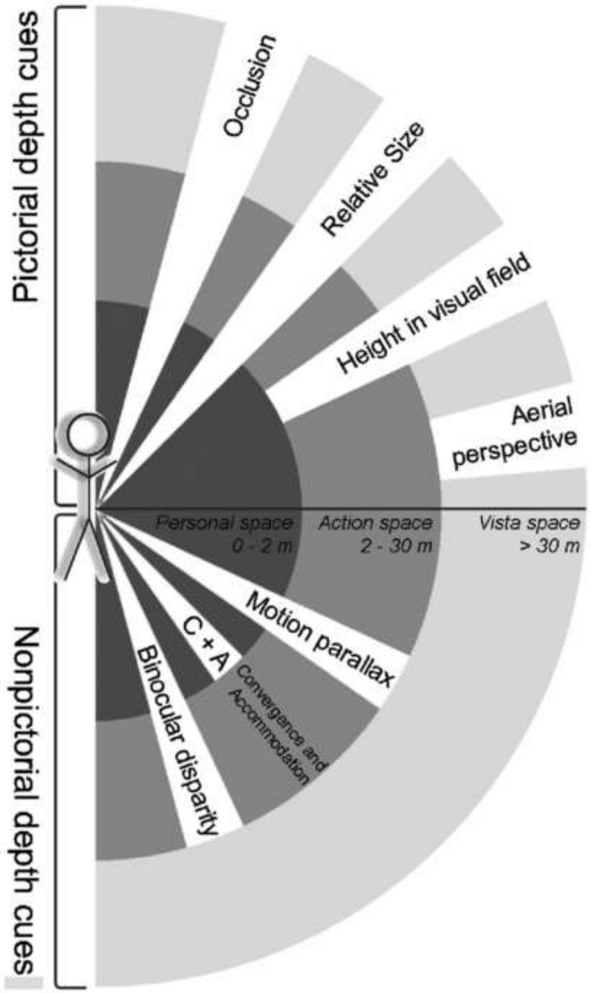
Distance and Depth Perception

Distance and Depth Perception

- Ability to retrieve distance information
  - Exocentric: Relationship between objects
  - Egocentric: Distance towards objects

- Combination of all depth cues enable an accurate perception

- Cue **dominance**
  - In case of ambiguity the stronger cue will be used for disambiguation
  - Increase in uncertainty and inaccuracy

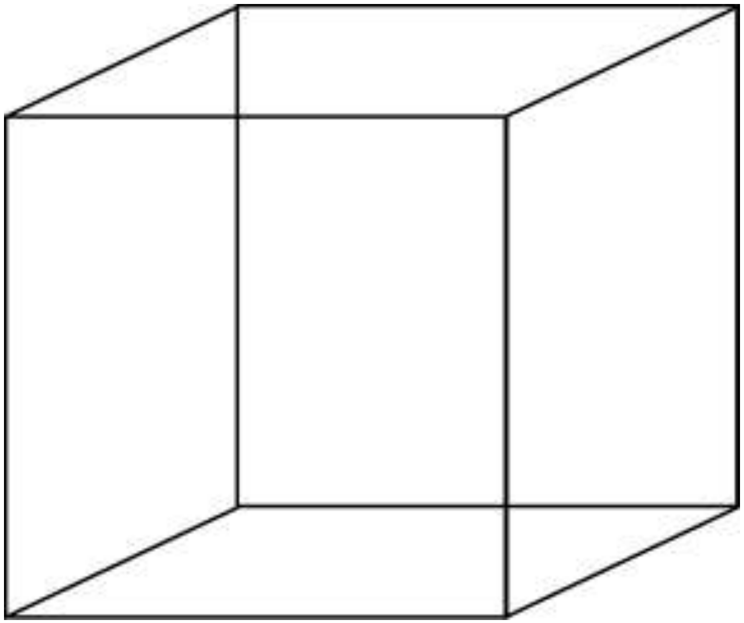


Drascic, D., & Milgram, P. (1996). Perceptual issues in augmented reality. Stereoscopic Displays and Virtual Reality Systems III, 2653, 123–134.

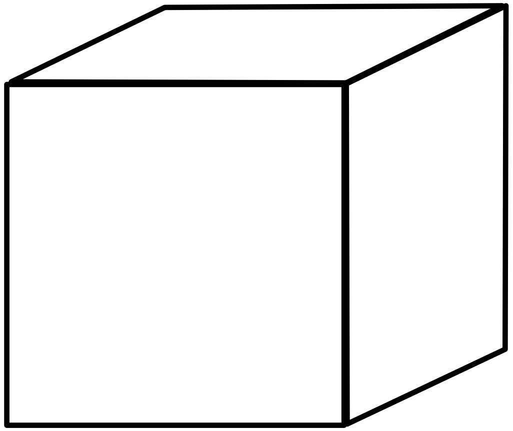
Renner, R. S., Velichkovsky, B. M., & Helmert, J. R. (2013). The perception of egocentric distances in virtual environments - A review. ACM Computing Surveys, 46(2), 1–40. https://doi.org/10.1145/2543581.2543590

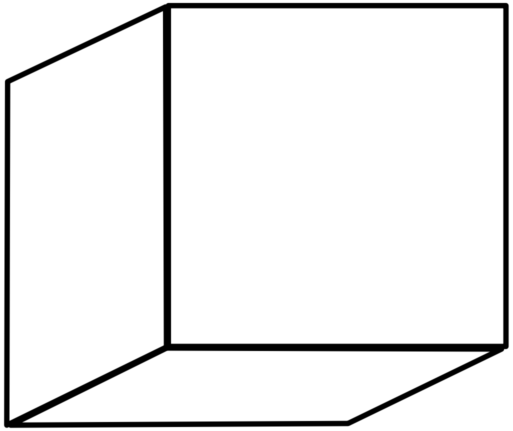
Pictorical Depth Cues

- Occlusion



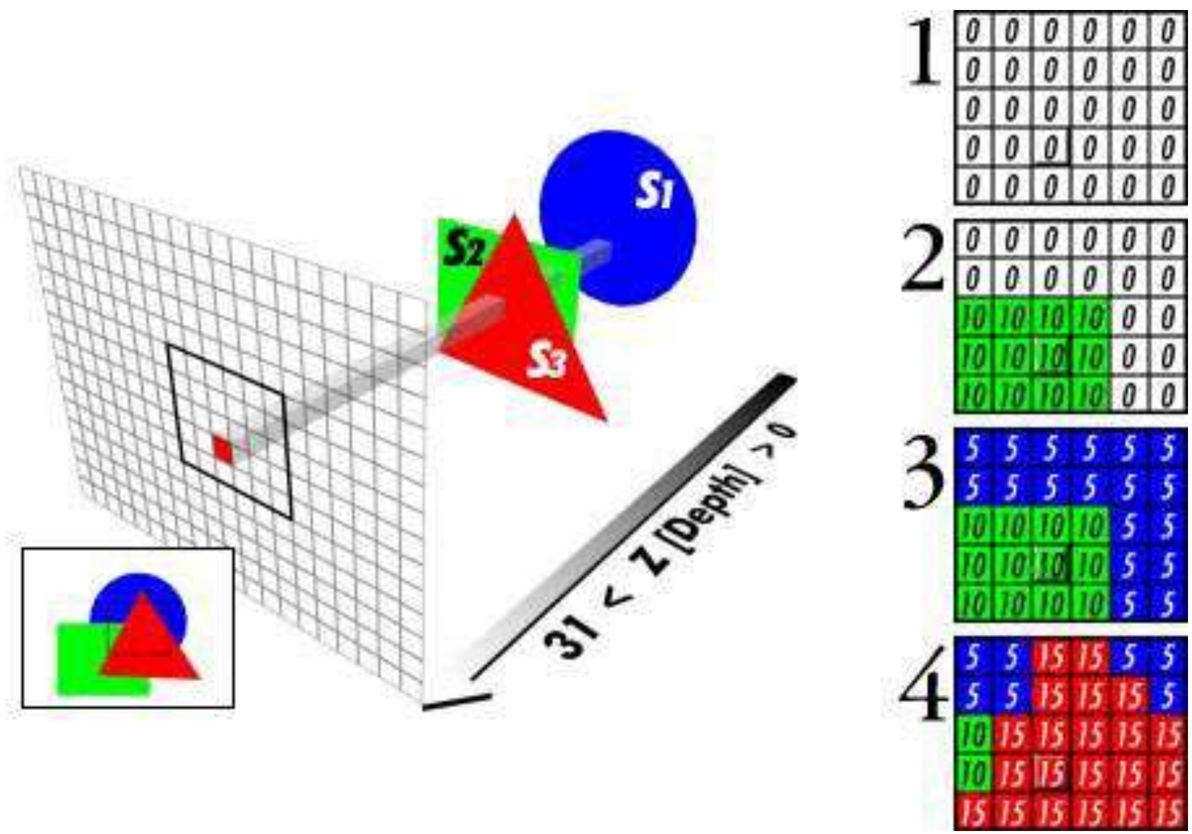
The Necker Cube





Pictorical Depth Cues

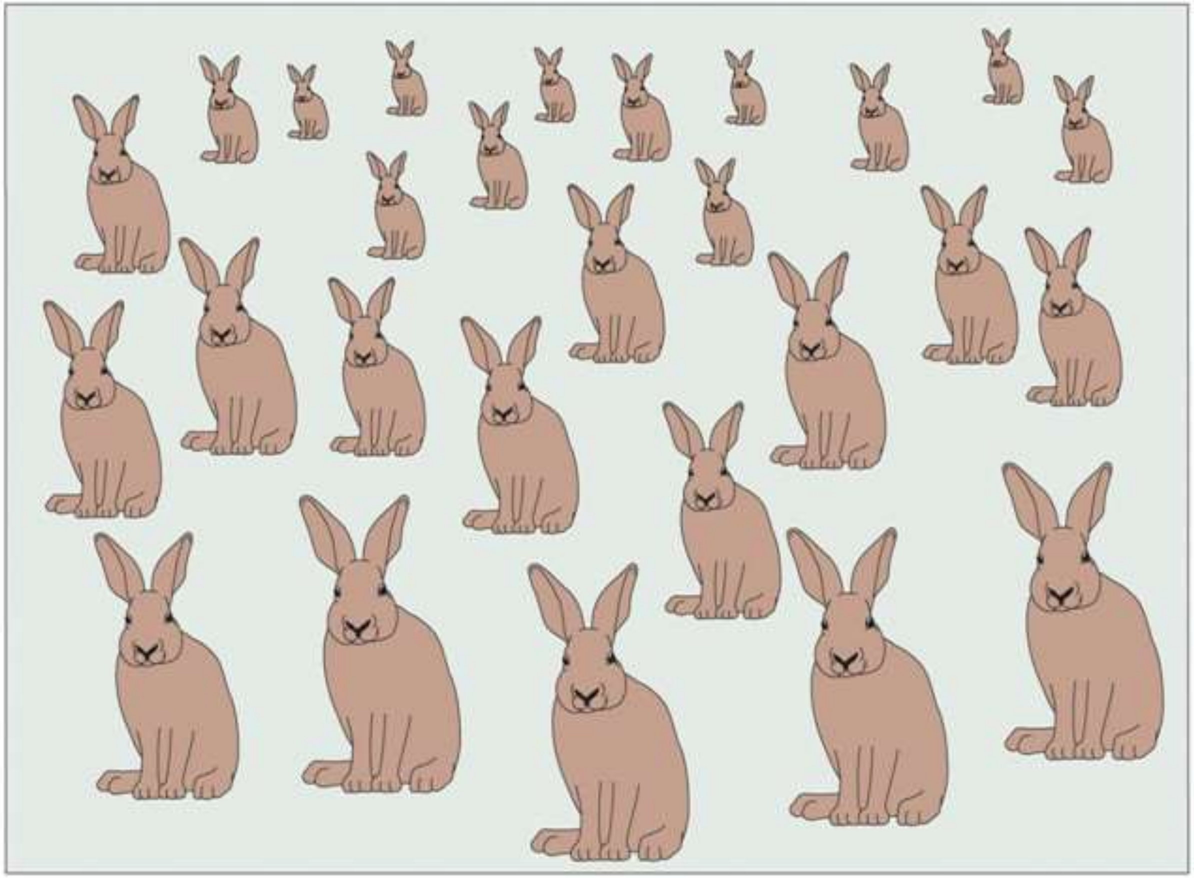
- Occlusion
  - Achieved using the Z-buffer algorithm in computer graphics



OpenGL

Pictorical Depth Cues

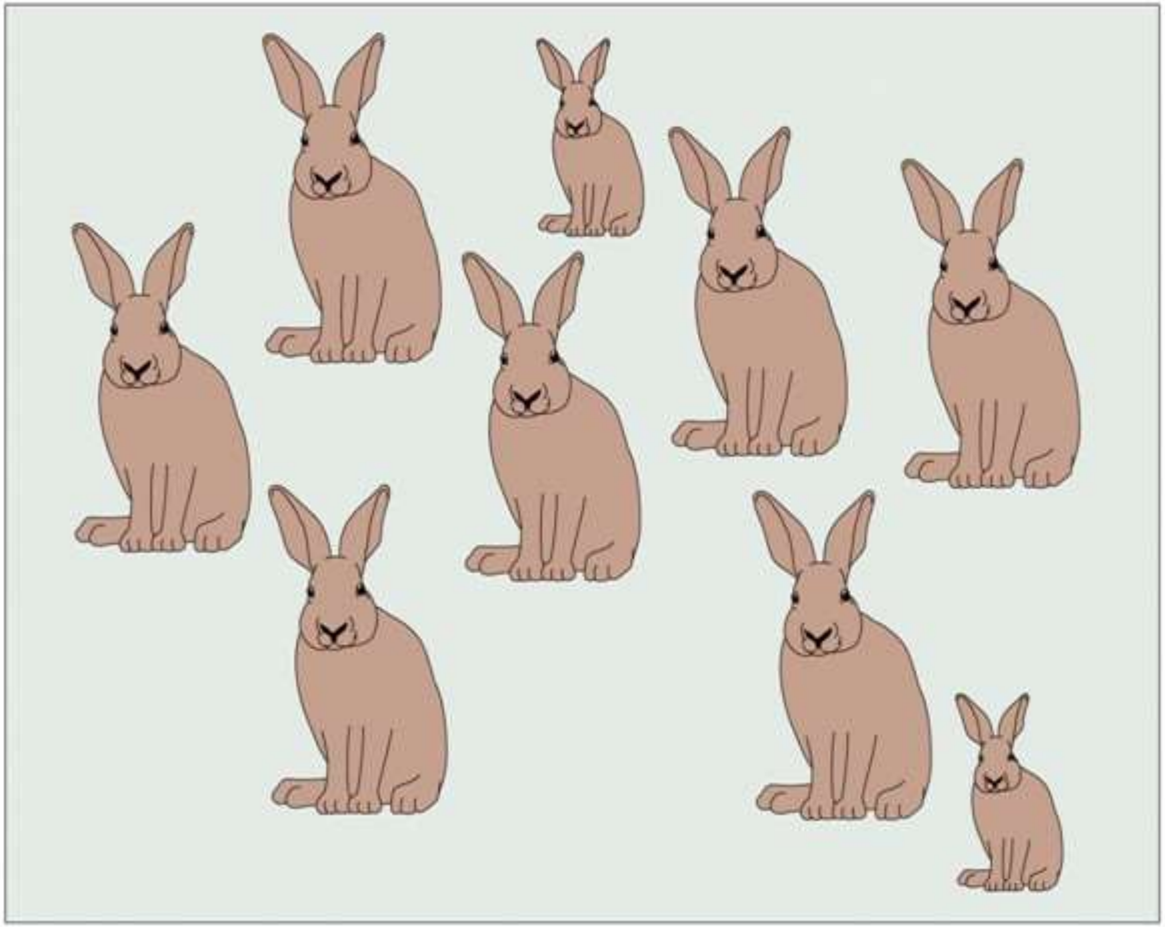
- Relative size



SENSATION AND PERCEPTION, Figure 6.7 © 2006 Sinauer Associates, Inc.

Pictorical Depth Cues

- Relative size



SENSATION AND PERCEPTION, Figure 6.10

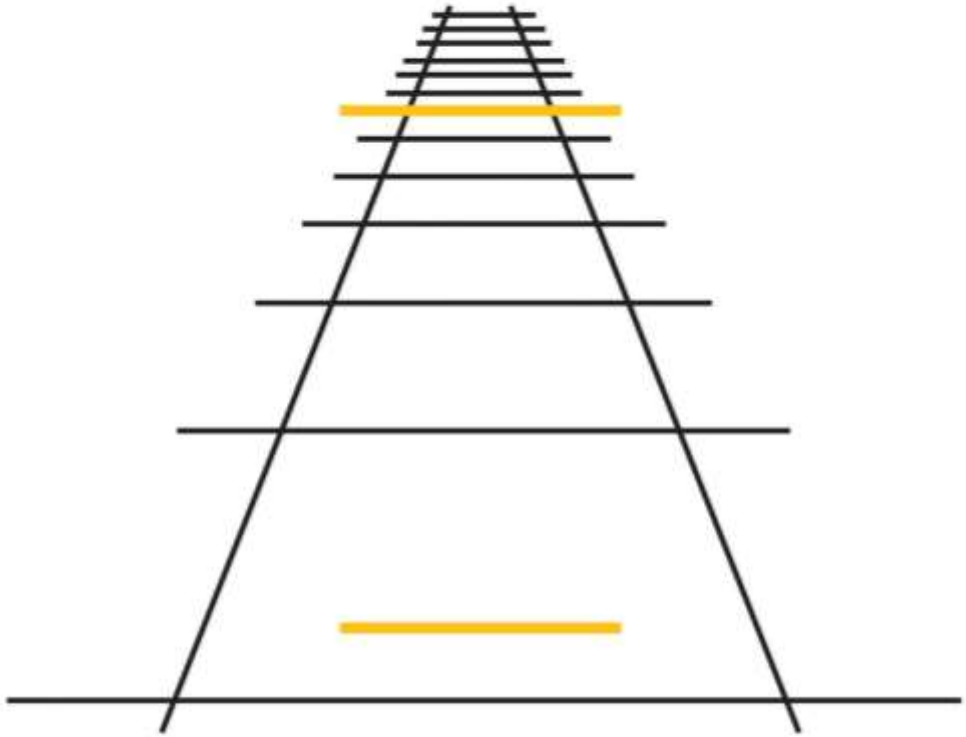
Pictorical Depth Cues

- Relative size - Perspective deformation

Pietro Perugino [Public domain], via Wikimedia Commons

Pictorical Depth Cues

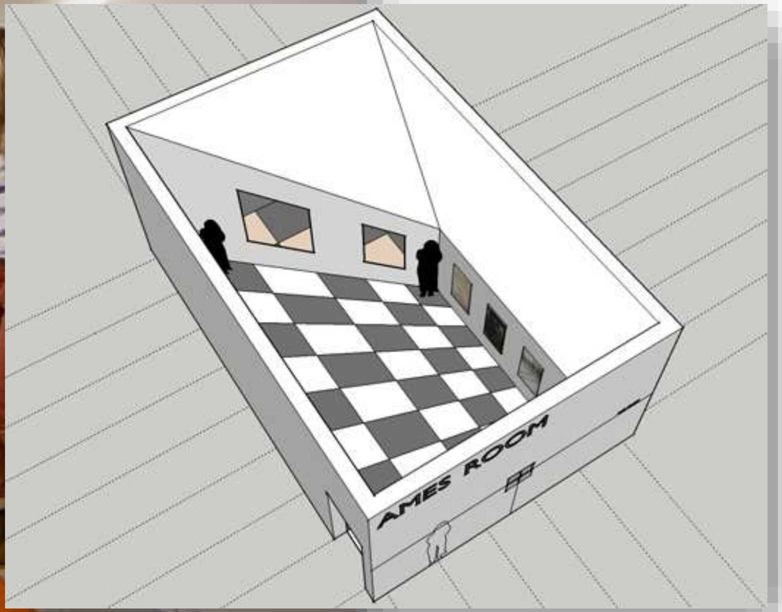
- Relative size - Perspective deformation
  - The ponzo illusion



Pictorical Depth Cues

- Relative size - Perspective deformation
  - The Ames room

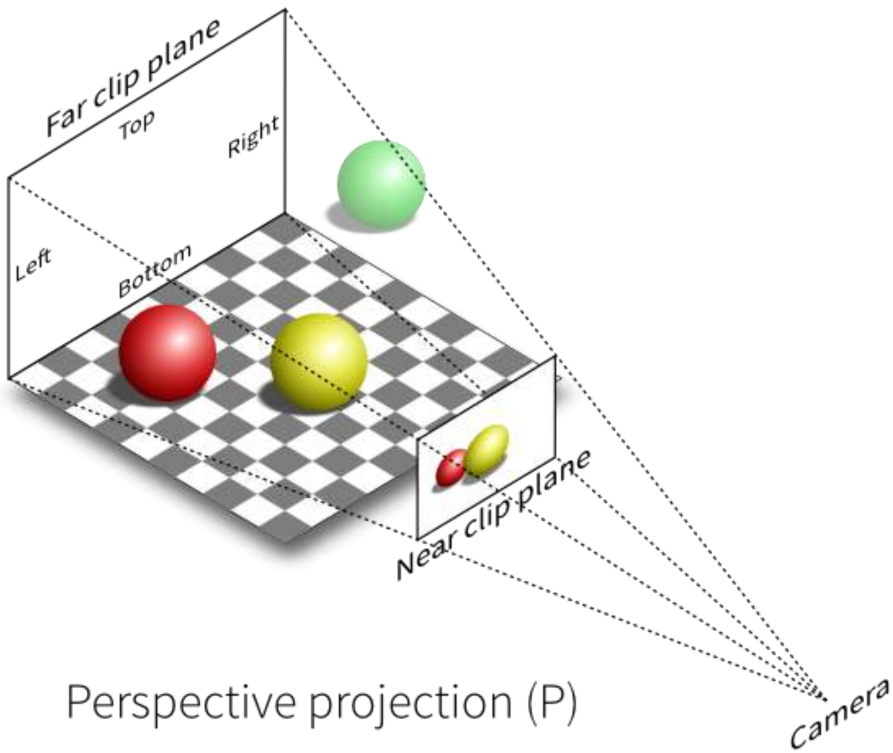
The Ames Room – picture by Tony Marsh



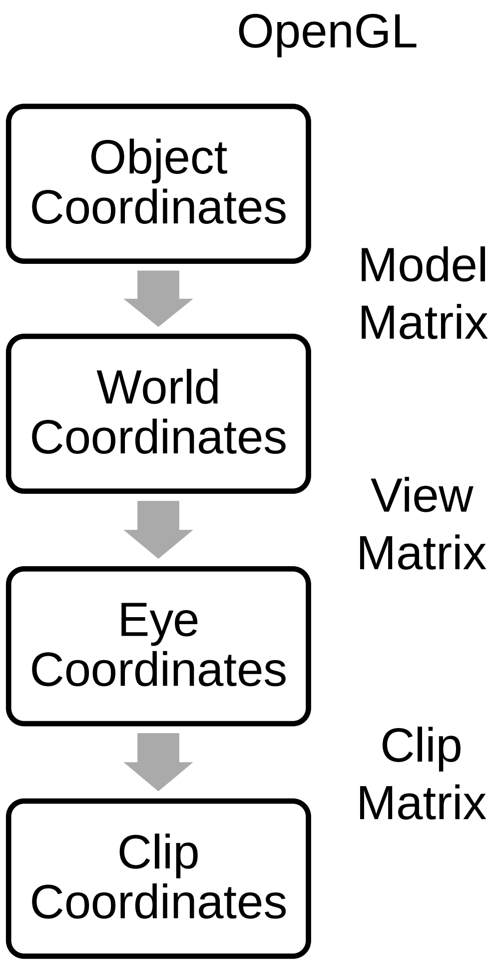
© Russell Light

Pictorical Depth Cues

- Relative size - Perspective deformation
  - Achieved through perspective projection



http://glumpy.readthedocs.io/en/latest/tutorial/cube-ugly.html



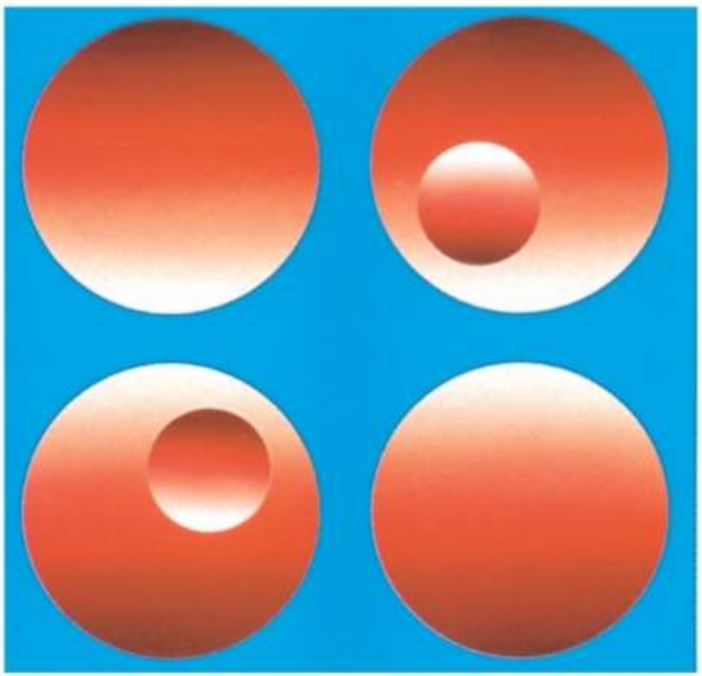
Pictorical Depth Cues

- Aerial perspective

SENSATION AND PERCEPTION, Figure 6.14 © 2006 Sinauer Associates, Inc.

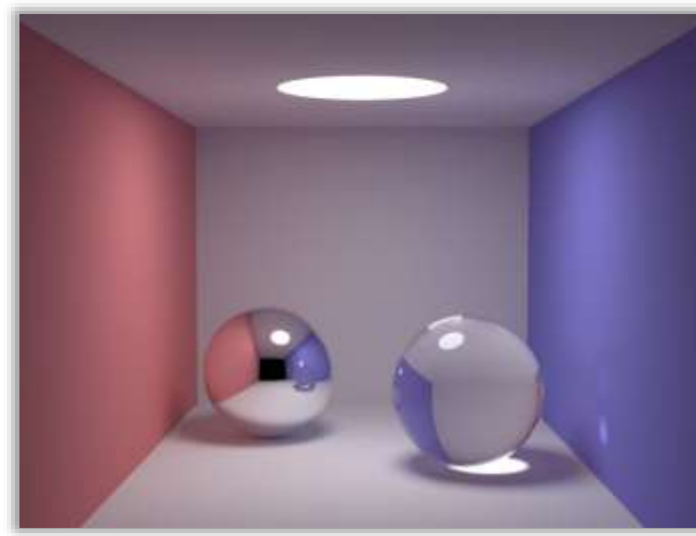
Pictorical Depth Cues

- Environment lighting (e.g. global illumination)



From "Perceiving Shape from Shading" by Vilayanur S. Ramachandran. Copyright © 1988 by Scientific American, Inc. All Rights Reserved. Photo © George V. Kelvin.

Unnumbered 13.7 Light and shadow
Myers: Exploring Psychology, Sixth Edition in Modules

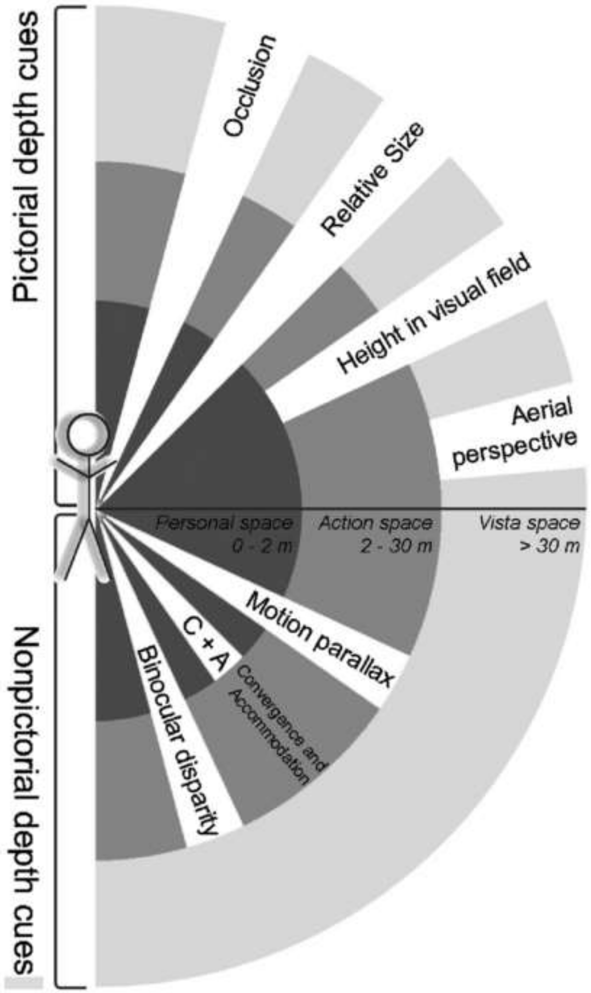


Distance and Depth Perception

- Ability to retrieve distance information
  - Exocentric: Relationship between objects
  - Egocentric: Distance towards objects

- Combination of all depth cues enable an accurate perception

- Cue **dominance**
  - In case of ambiguity the stronger cue will be used for disambiguation
  - Increase in uncertainty and inaccuracy



Drascic, D., & Milgram, P. (1996). Perceptual issues in augmented reality. Stereoscopic Displays and Virtual Reality Systems III, 2653, 123–134.

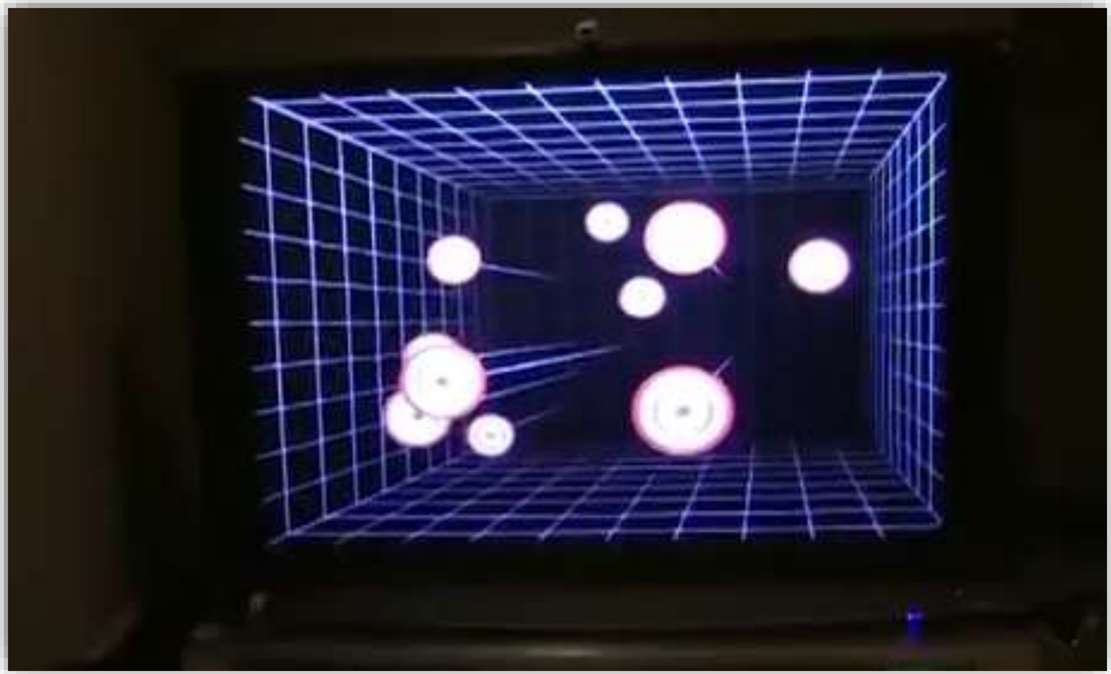
Renner, R. S., Velichkovsky, B. M., & Helmert, J. R. (2013). The perception of egocentric distances in virtual environments - A review. ACM Computing Surveys, 46(2), 1–40. https://doi.org/10.1145/2543581.2543590

Non-Pictorical Depth Cues

- Motion Parallax
  - Objects at different distances exhibit different horizontal motion speeds.

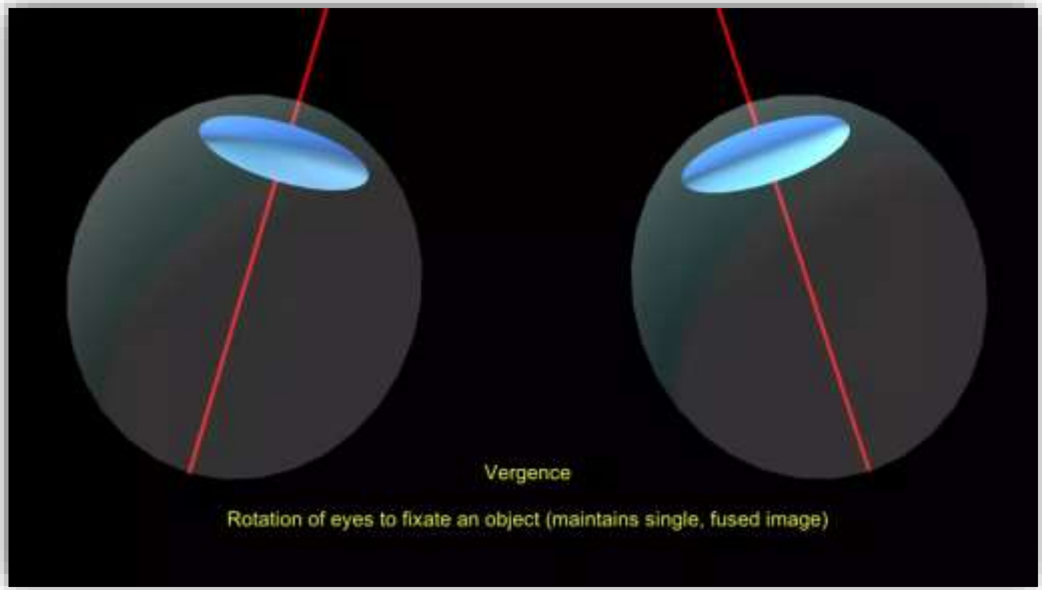
Non-Pictorical Depth Cues

- Motion Parallax
  - Objects at different distances exhibit different horizontal motion speeds.
  - View dependent 3D rendering



Non-Pictorical Depth Cues

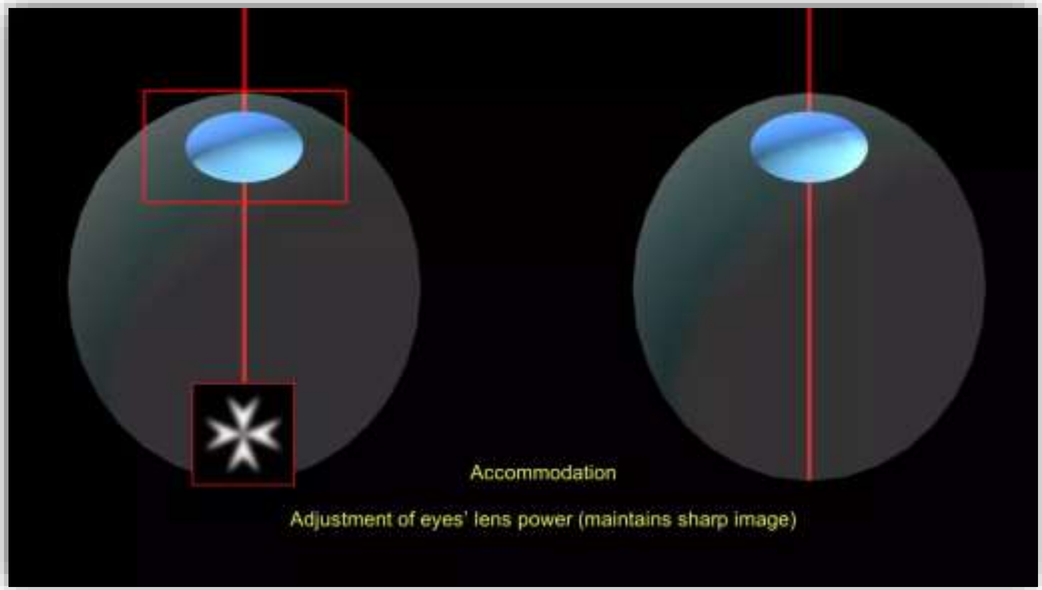
- Convergence

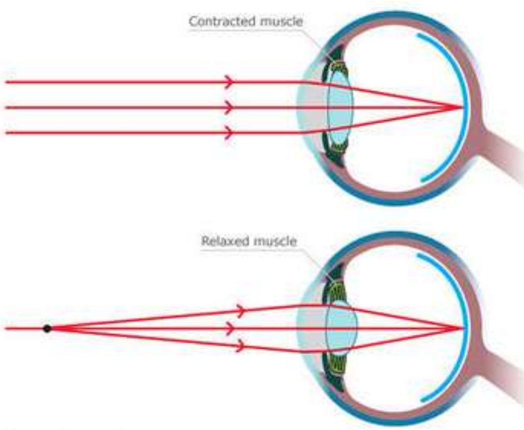


Accommodation and Comfort in Head-Mounted Displays". Koulieris, G. A., Bui, B., Banks, M. S., and Drettakis, G. (2017). ACM Transactions on Graphics
https://www.youtube.com/watch?time_continue=52&v=0vMbiu2llQY

Non-Pictorical Depth Cues

- Accommodation

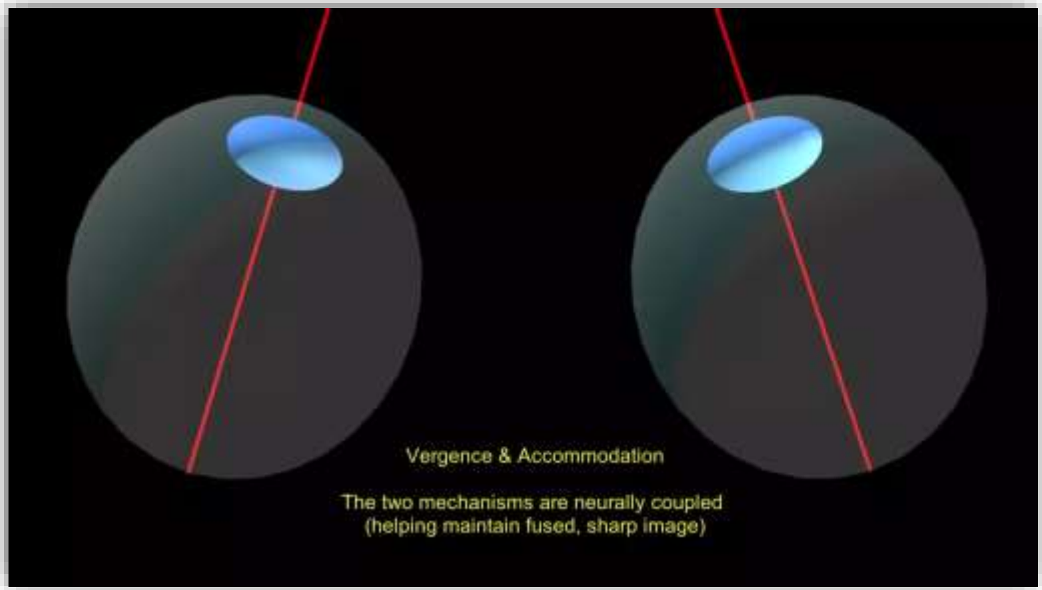


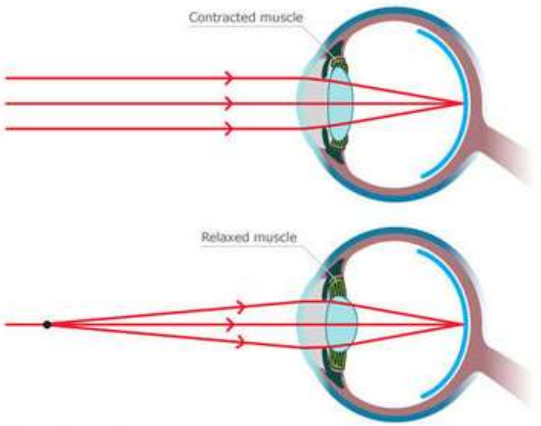


Accommodation and Comfort in Head-Mounted Displays". Koulieris, G. A., Bui, B., Banks, M. S., and Drettakis, G. (2017). ACM Transactions on Graphics
https://www.youtube.com/watch?time_continue=52&v=0vMbiu2lIQY

Non-Pictorical Depth Cues

- Accommodation

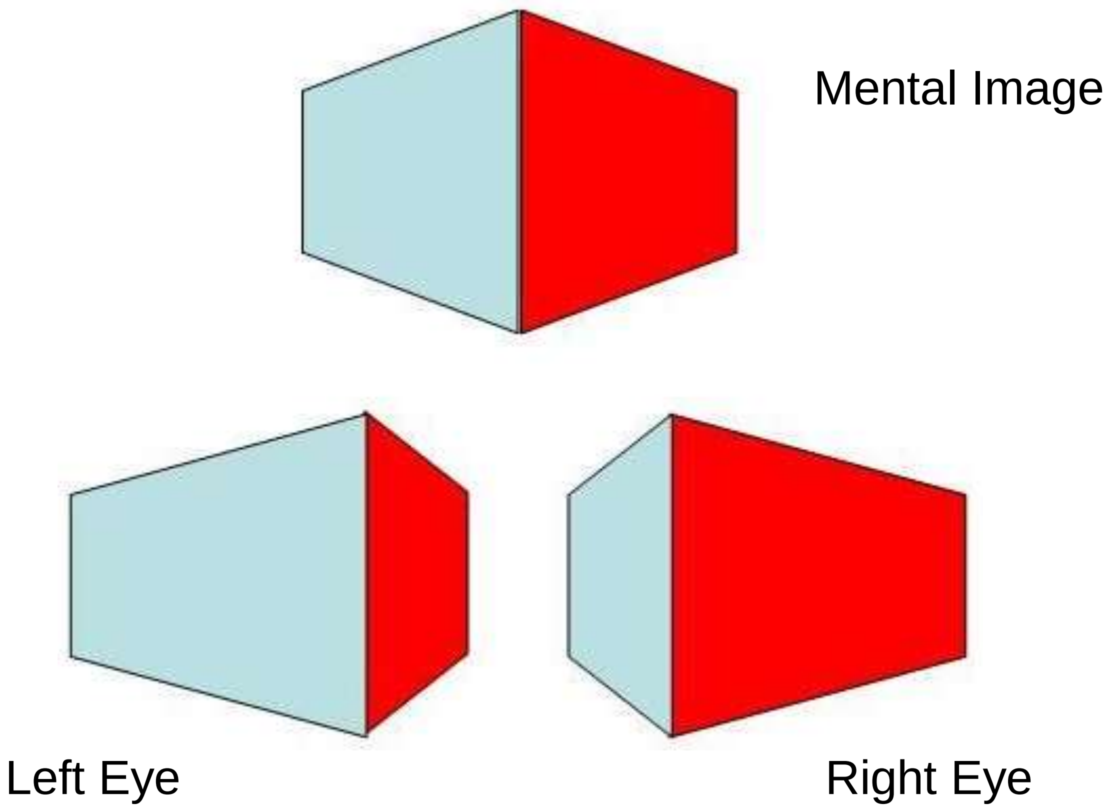




Accommodation and Comfort in Head-Mounted Displays". Koulieris, G. A., Bui, B., Banks, M. S., and Drettakis, G. (2017). ACM Transactions on Graphics
https://www.youtube.com/watch?time_continue=52&v=0vMbiu2lIQY

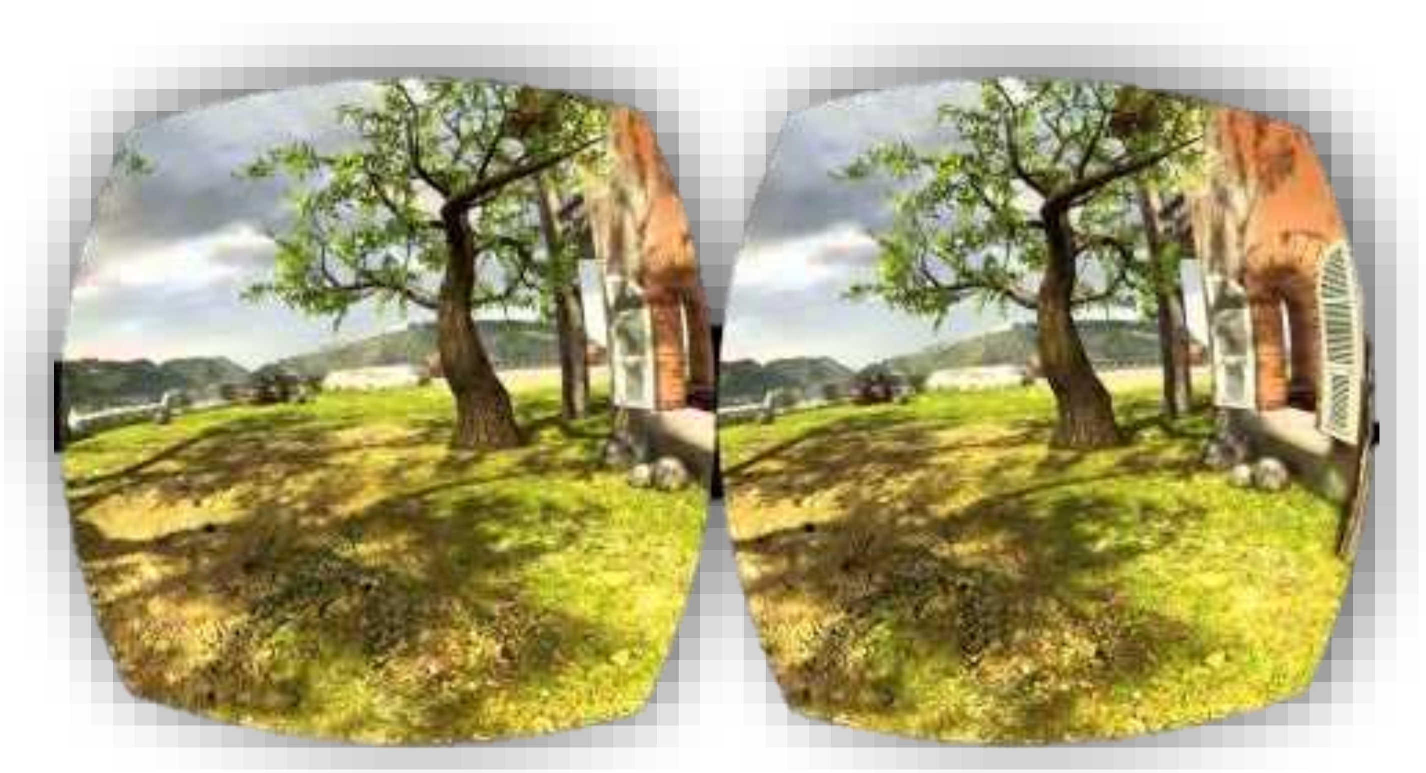
Non-Pictorical Depth Cues

- Binocular disparity



Non-Pictorical Depth Cues

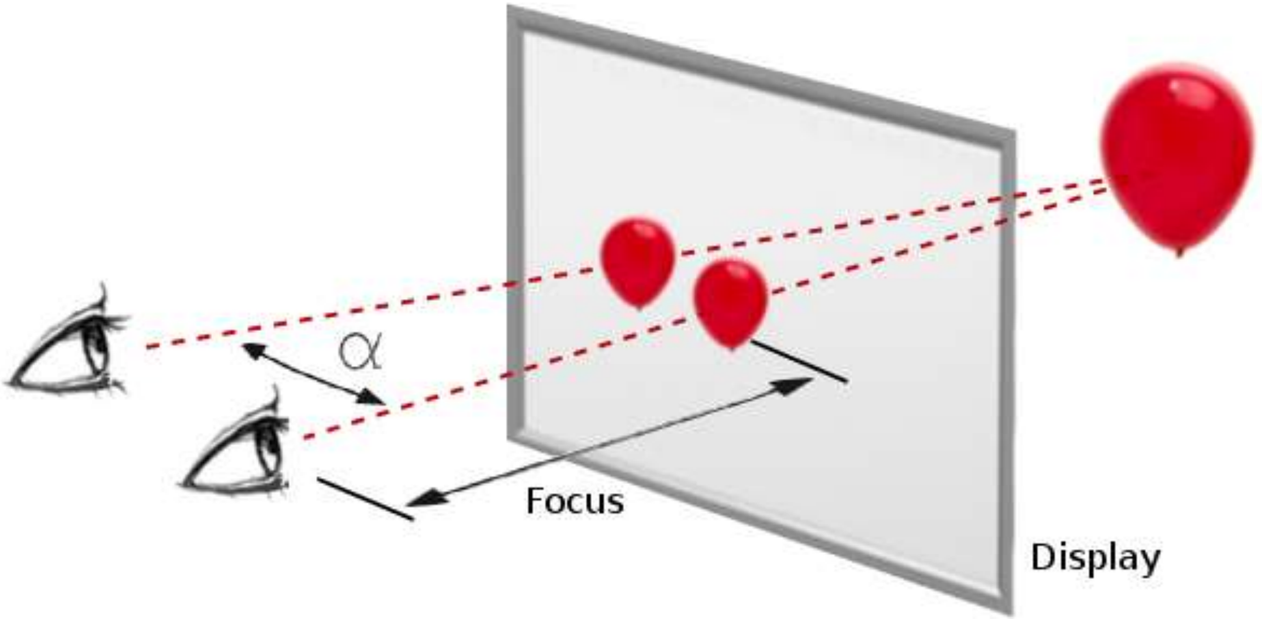
- Stereoscopic Rendering
  - One different image for each eye.



Oculus Rift. Tuscany Demo.

Non-Pictorical Depth Cues

- Stereoscopic Rendering
  - One different image for each eye.
  - Average Inter-Pupillary Distance (IPD) is 64mm



G. Bruder, F. Argelaguet, A. H. Olivier and A. Lécuyer, "Distance estimation in large immersive projection systems, revisited," *2015 IEEE Virtual Reality (VR)*, Arles, 2015, pp. 27-32.

Distance Perception

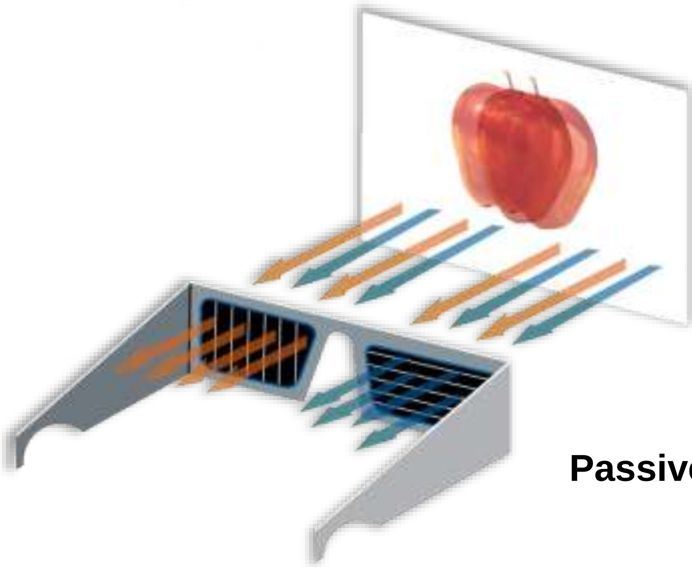
Visual Displays

Visual Displays

- Stereoscopic Rendering Technology
  - Time-multiplexing (Active Stereo)
  - Light polarization (Passive Stereo)
  - Color separation (Anaglyph Stereo)

Active

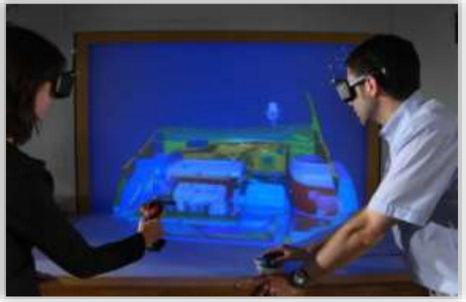
Anaglyph



Passive

Characteristics of Visual Displays

- Main specifications
  - Field of View
  - Field of Regard
  - Resolution and refresh rate
  - Monoscopic or stereoscopic
- Technologies
  - LCD / LED Screens (single / multiple)
  - Projection Systems
  - Head-Mounted Displays
  - Autostereoscopic Displays
  - “3D” Displays

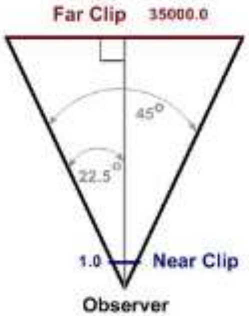


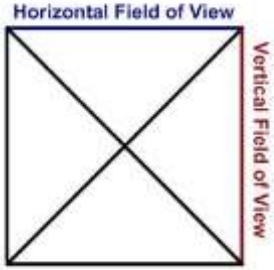
Head Mounted Displays

Ivan Sutherland HMD - 1965

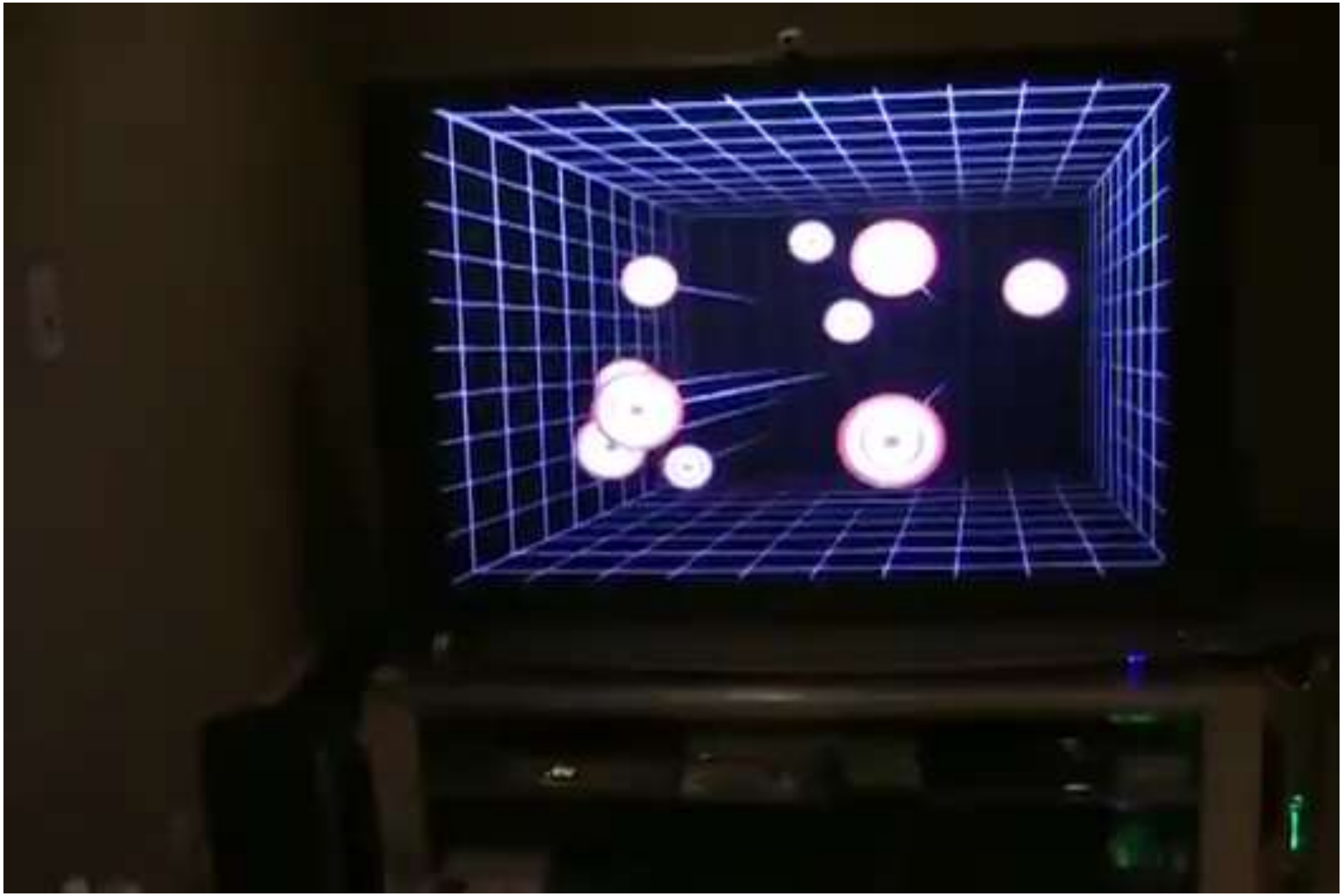
+ Resolution
+ Portable

Current HMDs





Fishtank



Projection Systems

WorkBench

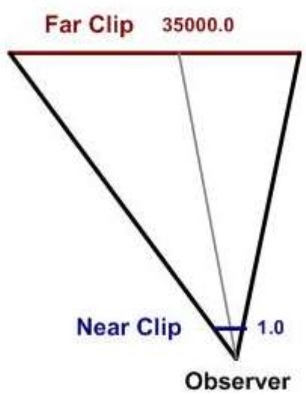
PowerWall

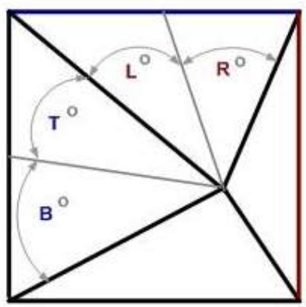
4-Sided CAVE

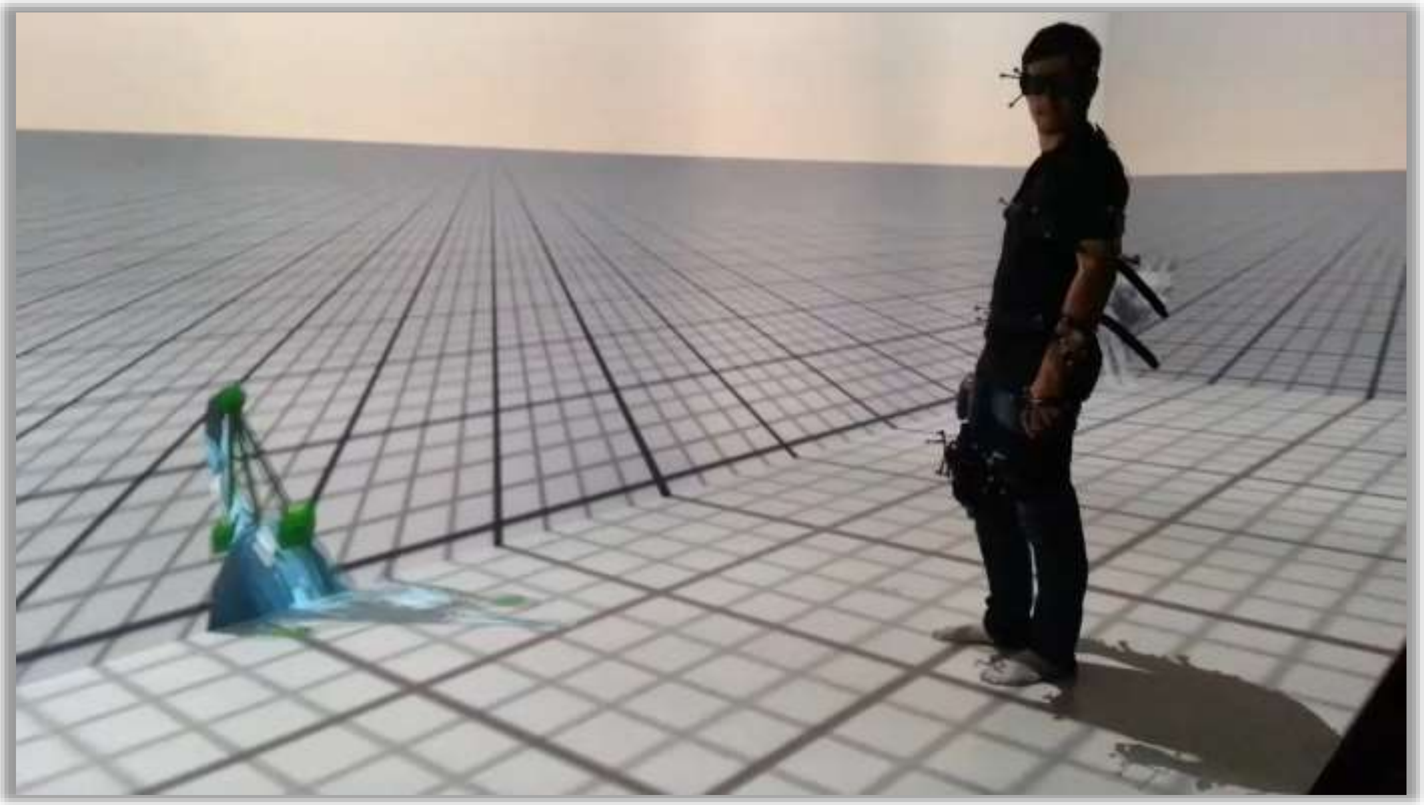
Tiled Display CAVE

Projection Systems

- Asymmetric View Frustum







Hand-Held Displays

Augmented Reality

Hand-Held Displays

See-through HMDs

- Mixing real and virtual content

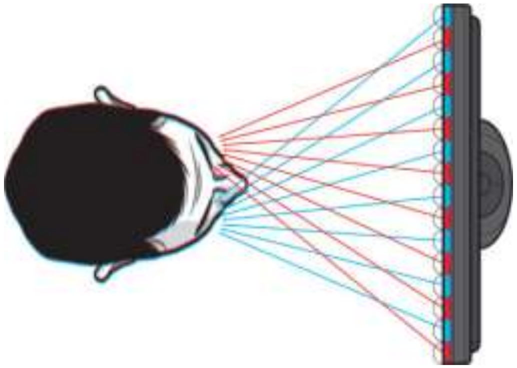
Microsoft HoloLens

Z800 Pro AR

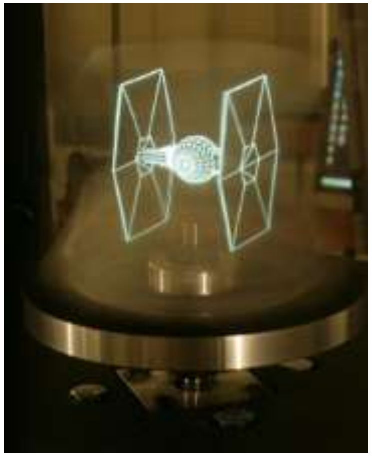
Magic Leap

See-through HMDs

Other Visual Displays



Autoestereoscopic Displays

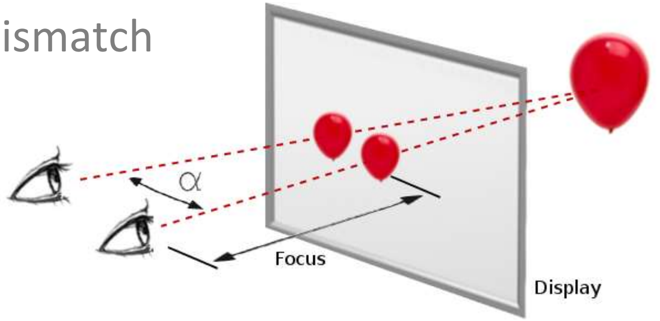


Volumetric Displays

Mirror-based Displays

Visual Perception in VR and AR

- Display technology can alter human visual perception
  - Miscalibration, accommodation/convergence mismatch
  - Virtual objects look closer than they are.
  - Alter object relationships



- Mismatch between real and virtual content
  - Inconsistent illumination
  - Inconsistent visibility

- J. P. Rolland, et al. Towards quantifying depth and size perception in virtual environments. Presence: Teleoperators & Virtual Environments, 4(1):24–49, 1995.
- J. A. Jones, et al. The effects of virtual reality, augmented reality, and motion parallax on egocentric depth perception. ACM Symposium on Applied Perception in Graphics and Visualization, pages 9–14. 2008
- E. Kruijff, et al. Perceptual issues in augmented reality revisited. IEEE International Symposium on Mixed and Augmented Reality, pages 3–12. 2010.

Perceptual adaptation

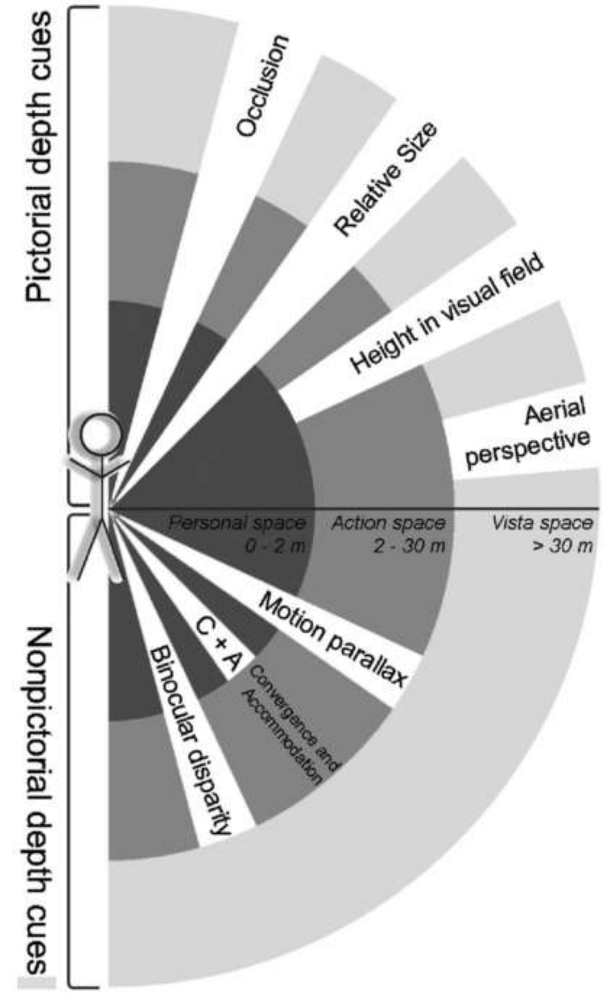
- Can our perceptions change?
- Example: Looking at the world upside down

Distance and Depth Perception

- Ability to retrieve distance information
  - Exocentric: Relationship between objects
  - Egocentric: Distance towards objects

- Combination of all depth cues enable an accurate perception

- Cue **dominance**
  - In case of ambiguity the stronger cue will be used for disambiguation
  - Increase in uncertainty and inaccuracy



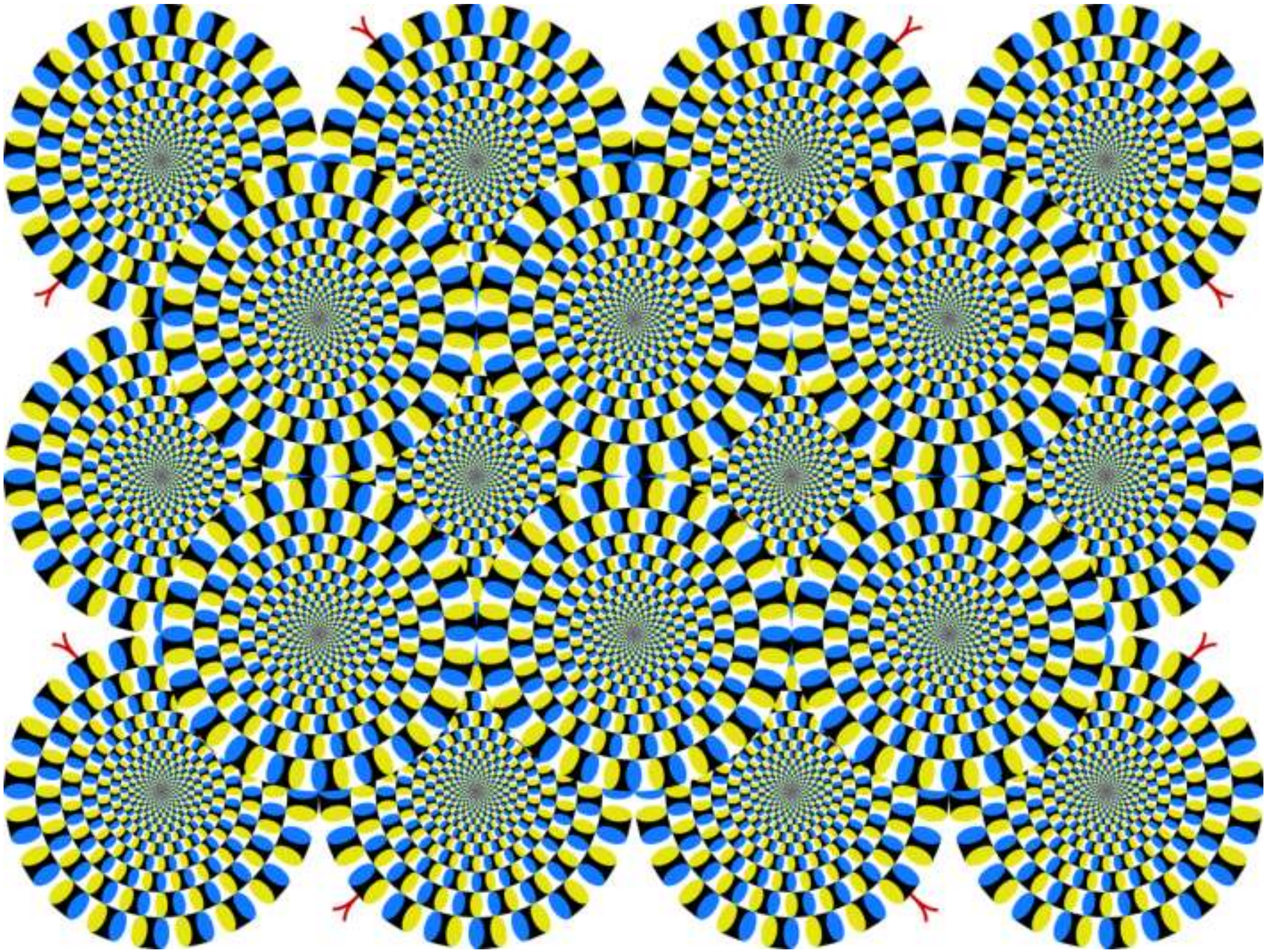
Drascic, D., & Milgram, P. (1996). Perceptual issues in augmented reality. Stereoscopic Displays and Virtual Reality Systems III, 2653, 123–134.

Renner, R. S., Velichkovsky, B. M., & Helmert, J. R. (2013). The perception of egocentric distances in virtual environments - A review. ACM Computing Surveys, 46(2), 1–40. https://doi.org/10.1145/2543581.2543590

Motion Perception

Visual System
Vestibular System
Motion Sickness

Motion illusions in Stationary Images



http://www.psy.ritsumei.ac.jp/~akitaoka/sakkaku-symposium2015-OFW.html

The Visual System and Optic Flow

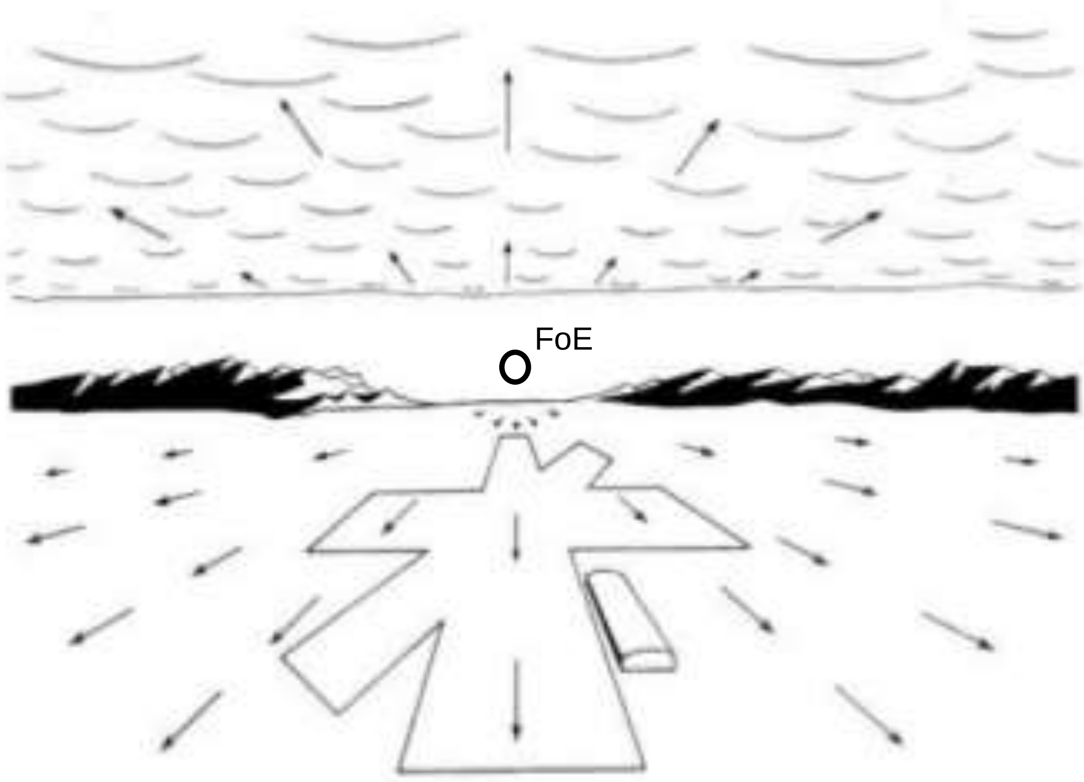
- The visual system infers motion from the changing pattern of light in the retinal image
  - The changing pattern can give the illusion of motion

- The optic flow provides information about the observer's heading and the relative distance to each surface in the world
  - Can generate unique an unambiguous interpretation of 3D motion and depth

- Close objects moving slowly can create an identical retinal image over time as a large, distance object when we are moving quickly
  - Enables relative speed/direction and distances estimates.

The Motion Flow Field

- Objects in the world change in predictable ways as we move
  - Rotational and translational motions
  - Retinal motion in the focus of expansion (FoE) is zero



The Motion Flow Field

- Objects in the world change in predictable ways as we move
  - Rotational and translational motions
  - Retinal motion in the focus of expansion (FoE) is zero
- Rotational: all the components in the flow field rotate the same amount around the axis of rotation regardless of distance.
  - E.g. Head rotations
- Translational: objects moves further away the expansion point
  - Closer points moves more than further points
  - Distance affects both the speed and the direction

Example

Example

Example

Vestibular System

- The inner ear is responsible for balance, equilibrium and orientation
  - The macula sacculi detects vertical acceleration.
  - The macula utriculi is responsible for horizontal acceleration.
- The vestibular system generates information about head movements in space, acceleration and posture.

https://en.wikipedia.org/wiki/Inner_ear

Simulation Sickness Effects

- The effects of Simulator Sickness are polysymptomatic and can vary in form and intensity between individuals
  - Complex problem to describe and define
- It can be evaluated through questionnaires such as the Simulator Sickness Questionnaire (SSQ) or indirect analysis of physiological signals such as blood pressure and heart rate
- The simulation sickness questionnaire considers three main areas
  - Nausea
  - Oculomotor Problems
  - Disorientation

Kenned R. et al. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness The International Journal of Aviation Psychology Vol. 3 , Iss. 3,1993

Explaining Simulation Sickness

- Three main theories try to explain the causes
  - Sensory Rearrangement Theory
  - Postural Instability Theory
  - Poison Theory

L. Rebenitsch et al., "Review on cybersickness in applications and visual displays," Virtual Reality, vol. 20, no. 2, pp. 101–125, 2016.

The Sensory Rearrangement Theory

- One main premise
  - All situations that provoke Motion Sickness are characterized by a sensory rearrangement condition in which signals transmitted by the visual and vestibular systems are in disagreement or dissociation with each other and with what is expected from previous experiences.

- When there is a dissociation between these elements and the sensory expectation is frustrated (based on previous experiences), the effects of Motion Sickness arise.
  - Effects only manifest themselves when there are movements with speed change (acceleration), since the vestibular system only reacts to angular and linear accelerations.

J. T. Reason, "Motion sickness adaptation: a neural mismatch model." Journal of the Royal Society of Medicine, vol. 71, no. 11, p. 819, 1978.
Y. Fang, R. Nakashima, K. Matsumiya, I. Kuriki, and S. Shioiri, "Eyehead coordination for visual cognitive processing," PloS one, vol. 10, no. 3, 2015.

The Postural Instability Theory

- One of the primary behavioral goals in humans is to maintain postural stability in the environment.

- Motion Sickness is not caused by all visual-vestibular dissociations but because the individual is unable to maintain appropriate postures, in order to compensate external stimuli.
  - The more unstable the body posture and the longer the duration of postural instability, the more severe the symptoms will be.

- The postural instability theory can be seen as a more restrictive SRT, where the only relevant factor for Motion Sickness is that the vestibular system can not respond to external stimuli.

Gary E. Riccio and Thomas A. Stoffregen. An Ecological Theory of Motion Sickness and Postural Instability. Ecological Psychology, 3(3):195-240, 1991.

The Poison Theory

- The poison theory attempts to provide an explanation for why motion sickness and cybersickness occur from an evolutionary standpoint
- The Poison theory proposes that symptoms such as nausea are caused by an incorrect application of the body's defense mechanisms against poisoning
  - The physiological defense is to expel food from the stomach acting as an early warning system which enhances survival
- It lacks predictive power and makes no determination for why people who get sick in virtual environments do not always have an emetic response

M. Treisman, "Motion sickness: an evolutionary hypothesis," Science, vol. 197, no. 4302, pp. 493–495, 1977.

Contributing Factors to Cybersickness in VE

- Display and Technology Issues
  - Position Tracking Error
  - Latency
  - Flicker

- Individual Factors
  - User’s role
  - Gender
  - Age
  - Illness

Decreasing Simulation Sickness in VE

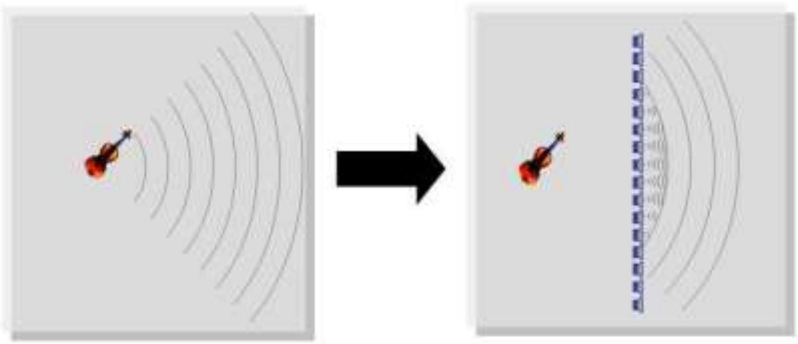
- User Adaptation
- Rest Frames
- Well-designed virtual navigation techniques
- Direct vestibular stimulation

Human Perception

Other displays

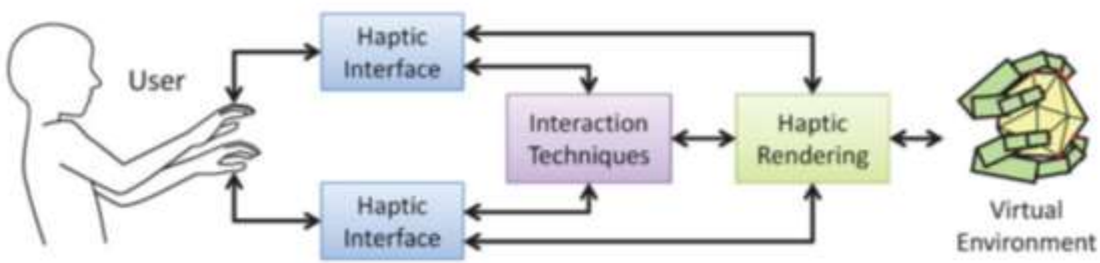
Auditory Displays

- Technologies
  - Binaural Rendering (Headphones)
  - Wave field synthesis (Speaker Arrays)
- Usages
  - Localization. (Spatial information)
  - Sensory substitution. (Button press)
  - Sonification. (Exploration of a dataset)



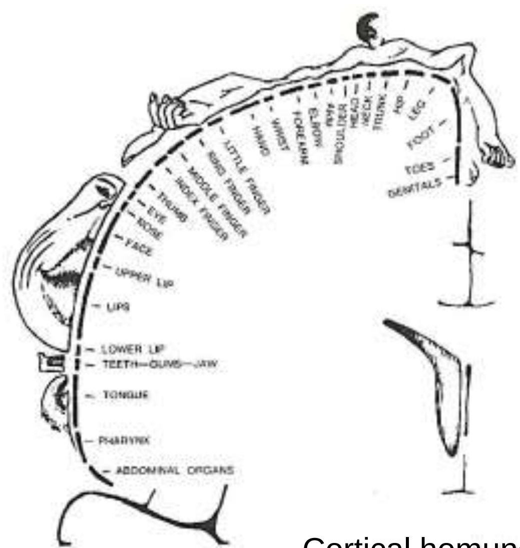
Haptic Displays

➤ Provide the user with the sense of touch



➤ Haptic cues

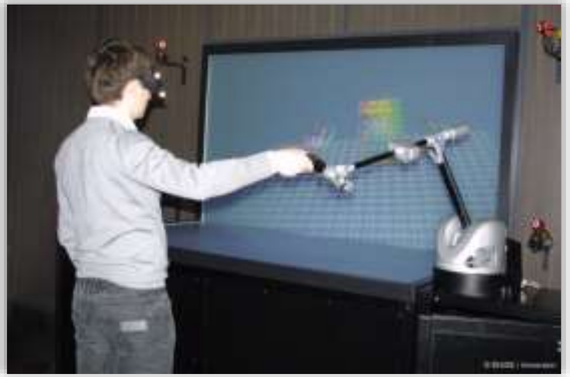
- Kinesthetic - Body
- Tactile - Skin



Cortical homunculus

Haptic Displays (Kinesthetic)

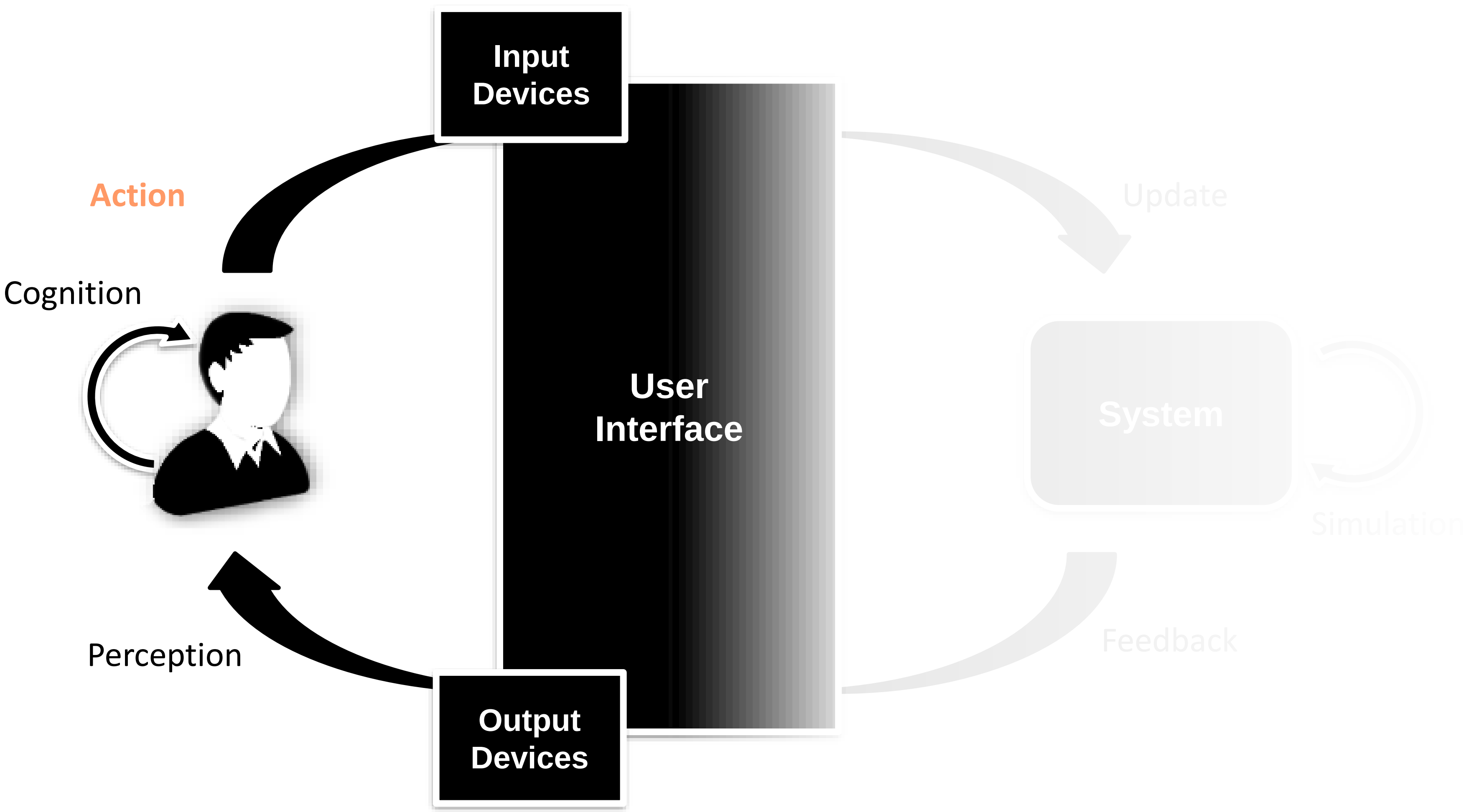
- Classification
  - Single point grounded
  - Single point mobile
  - Multi-finger body-based
  - Multi-finger grounded
- Physical Models
  - Point or rigid bodies
  - Rigid hand models
  - Deformable hand models



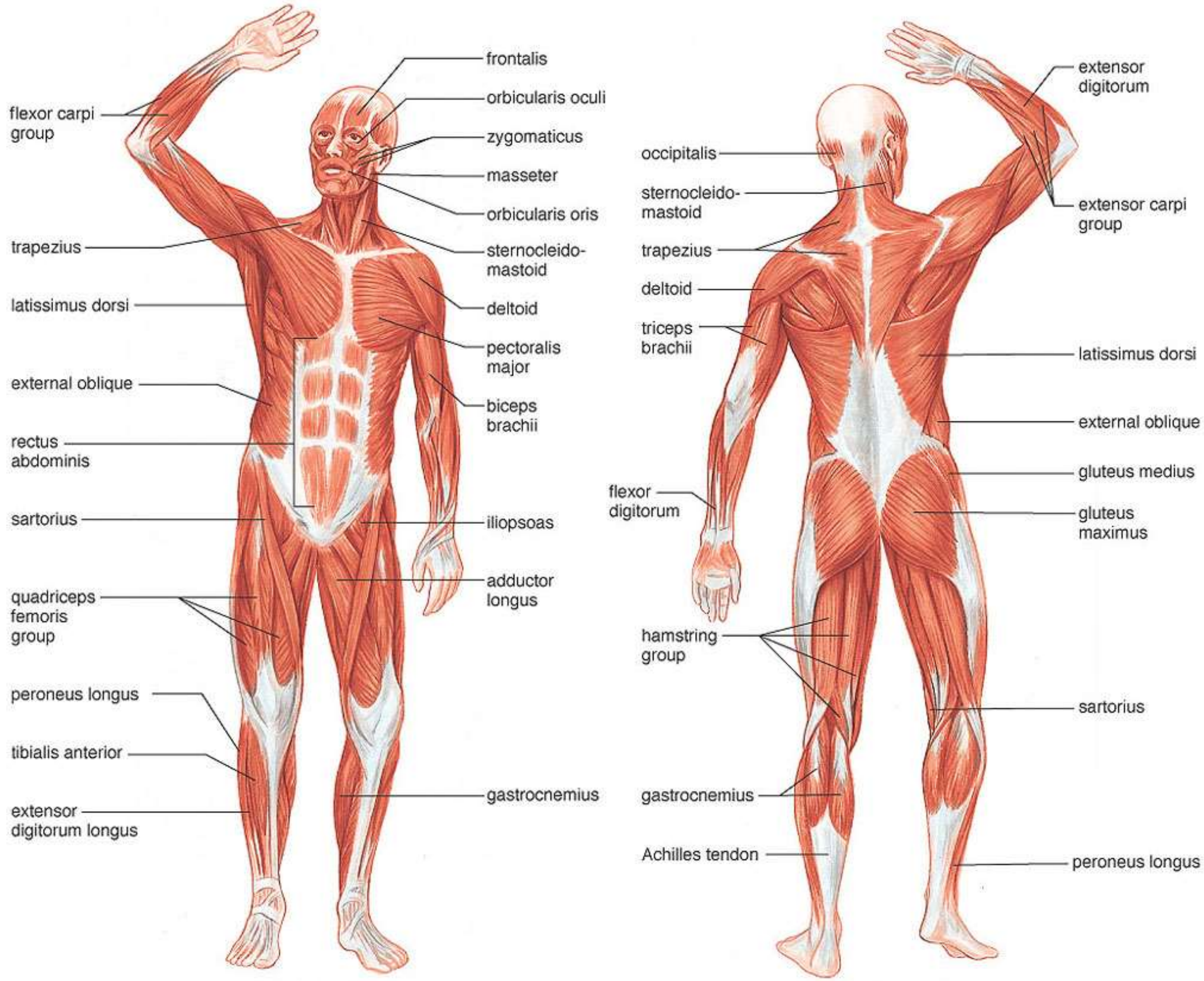
Motor Control

Human Pointing Models

The Interaction Loop



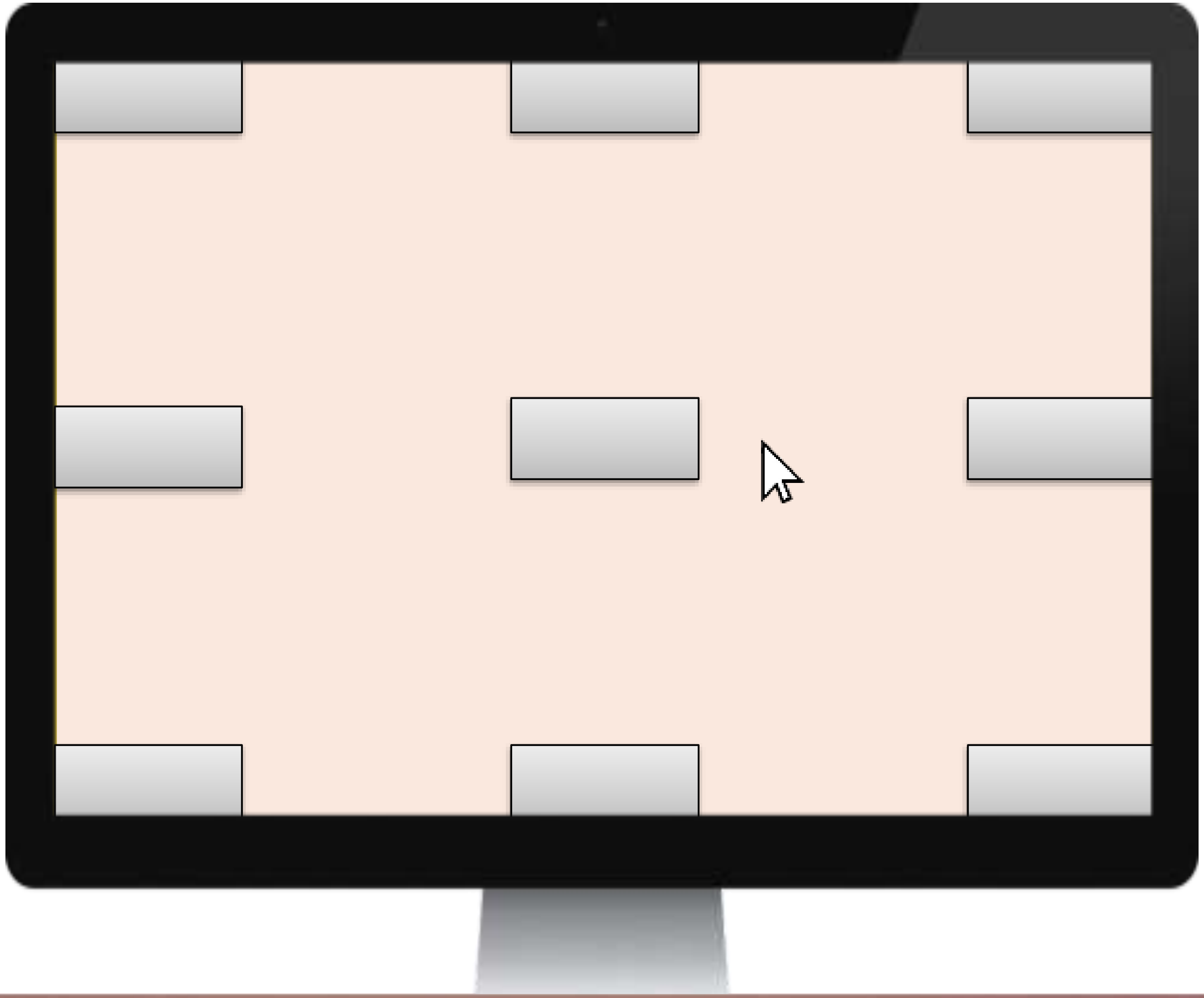
Muscular System



a. Anterior view

b. Posterior view

Question



Fitts' Law

- Human psychomotor behavior model which has been widely adopted in numerous areas including HCI.
- Estimates the time required to perform an aimed movement considering only the physical properties underlying the acquisition task.

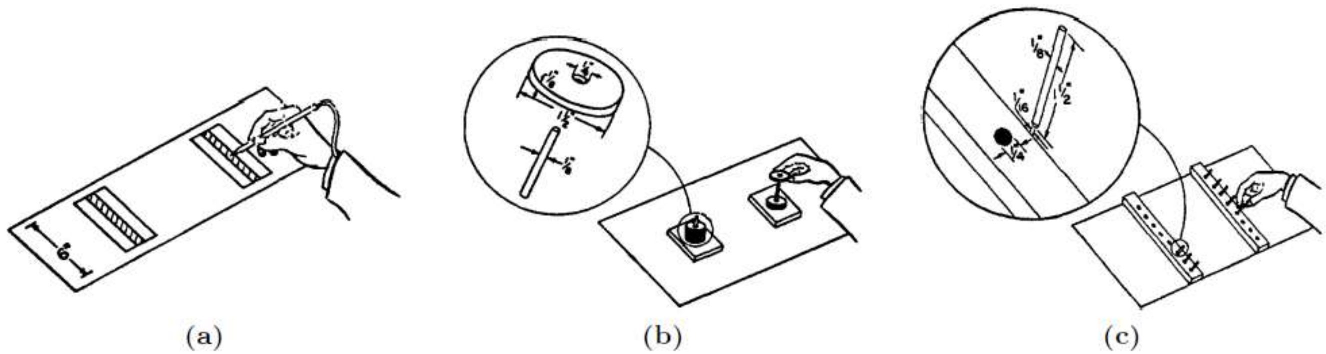


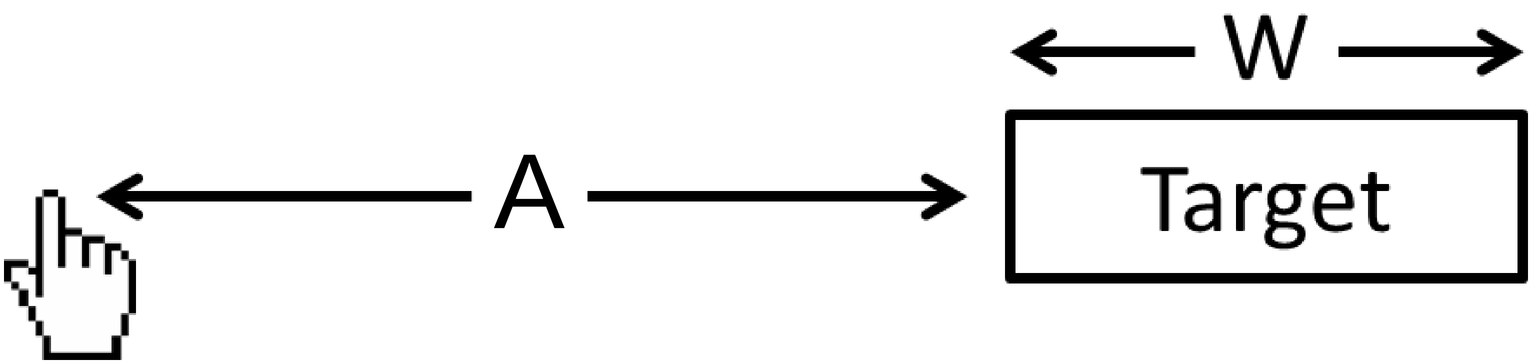
Figure 2.2: *Original Fitts' experiments. (a) Reciprocal tapping task. Participants had to hit repeatedly both center plates (stripped), without hitting the error plates surrounding the center plates. (b) Disc transfer task. Participants had to transfer eight washers (one at a time) from the right to the left pin. (c) Pin transfer task. Participants had to transfer each pin from one side to another.*

Fitts, Paul M. "The information capacity of the human motor system in controlling the amplitude of movement." *Journal of experimental psychology* 47.6 (1954): 381.

Fitts' Law

- Fitts' law estimates the mean movement time (*MT*) considering the distance to the target (*A*) and the target size (*W*). The regression coefficients *a* and *b* are computed experimentally.

$$MT = a + b\log_2\left(\frac{A+W}{W}\right)$$



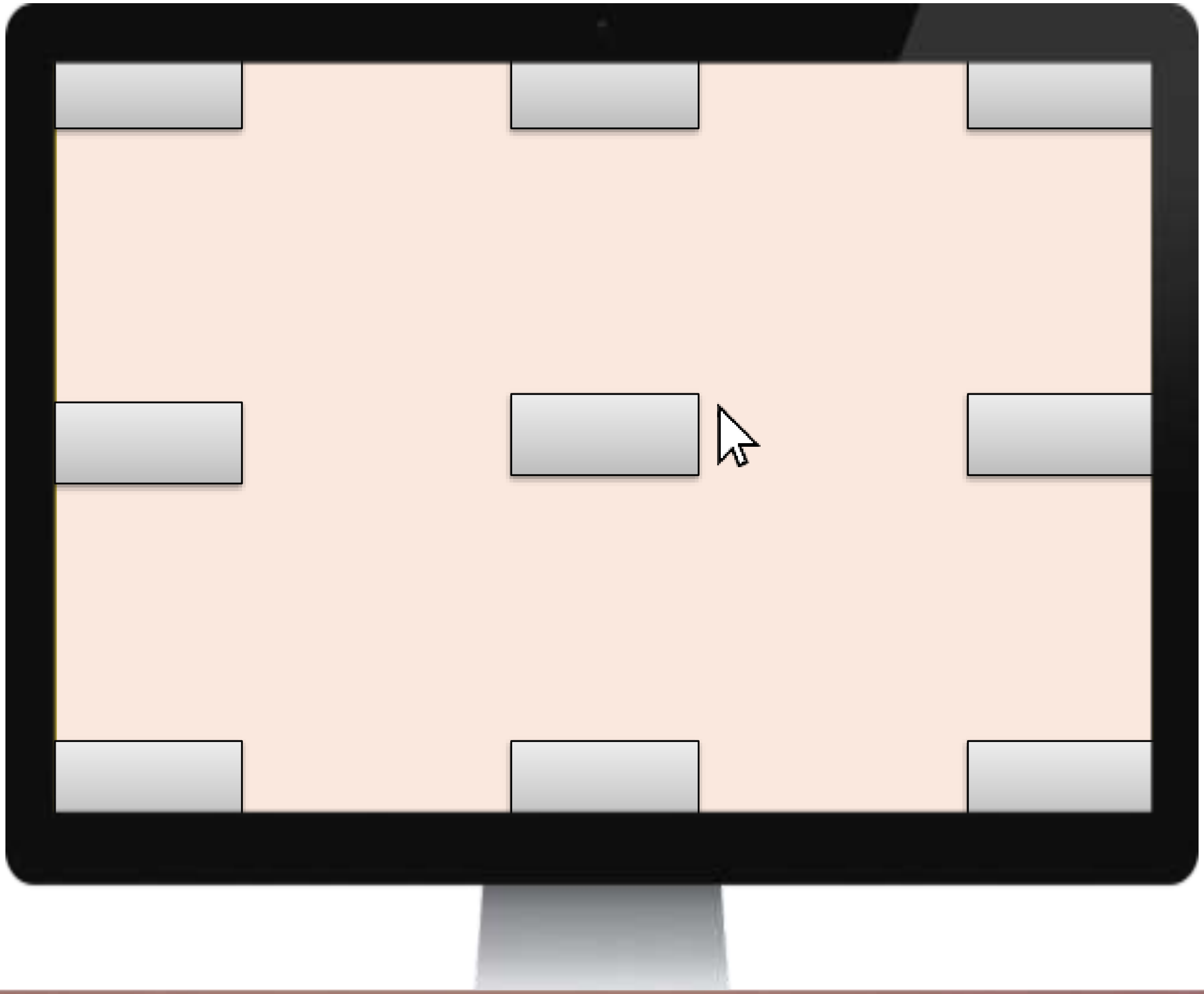
Fitts' Law

- Fitts' law estimates the mean movement time (*MT*) considering the distance to the target (*A*) and the target size (*W*). The regression coefficients *a* and *b* are computed experimentally.

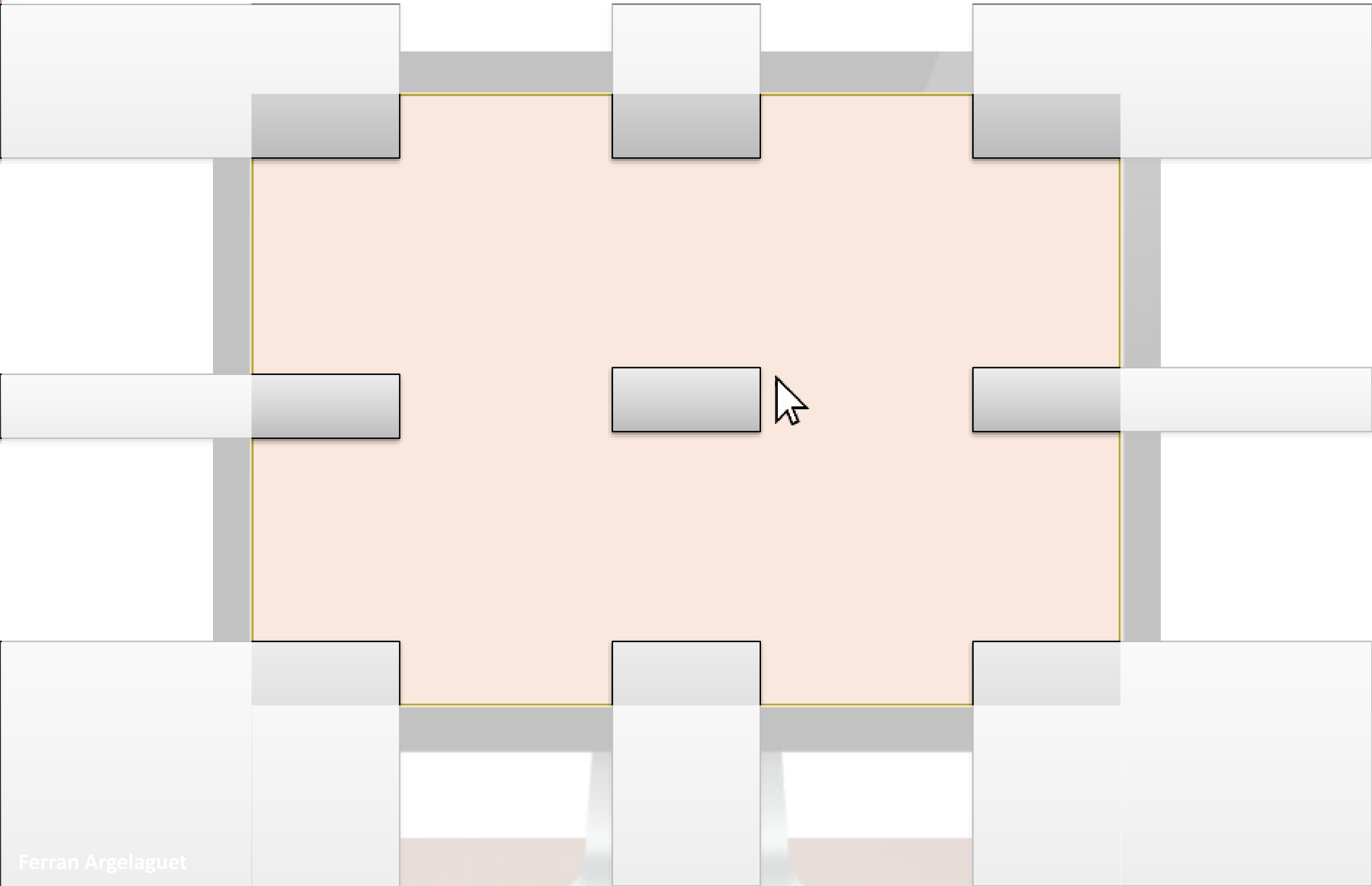
$$MT = a + b \log_2 \left(\frac{A + W}{W} \right)$$

- The intercept a is sensitive to additive factors like reaction times (e.g. time to locate the target or time to trigger the selection confirmation).
- The inverse of the slope 1/b is the index of performance (IP) expressed in seconds/bit.
  - Dependent on the user and the involved muscle groups.

Question again



Fitts' Law



Optimized Initial Impulse Model

- Acquisition tasks are subdivided in a two-step movement
  - Ballistic phase. A fast and inaccurate movement is made towards the target.
  - Correction phase. If the target is not acquired, iterative slow correction movements are executed until the target is acquired

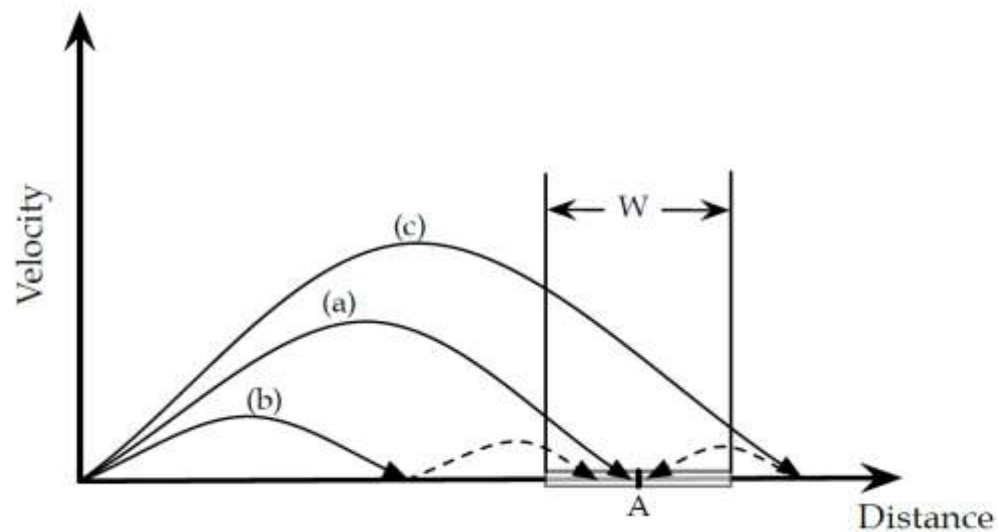
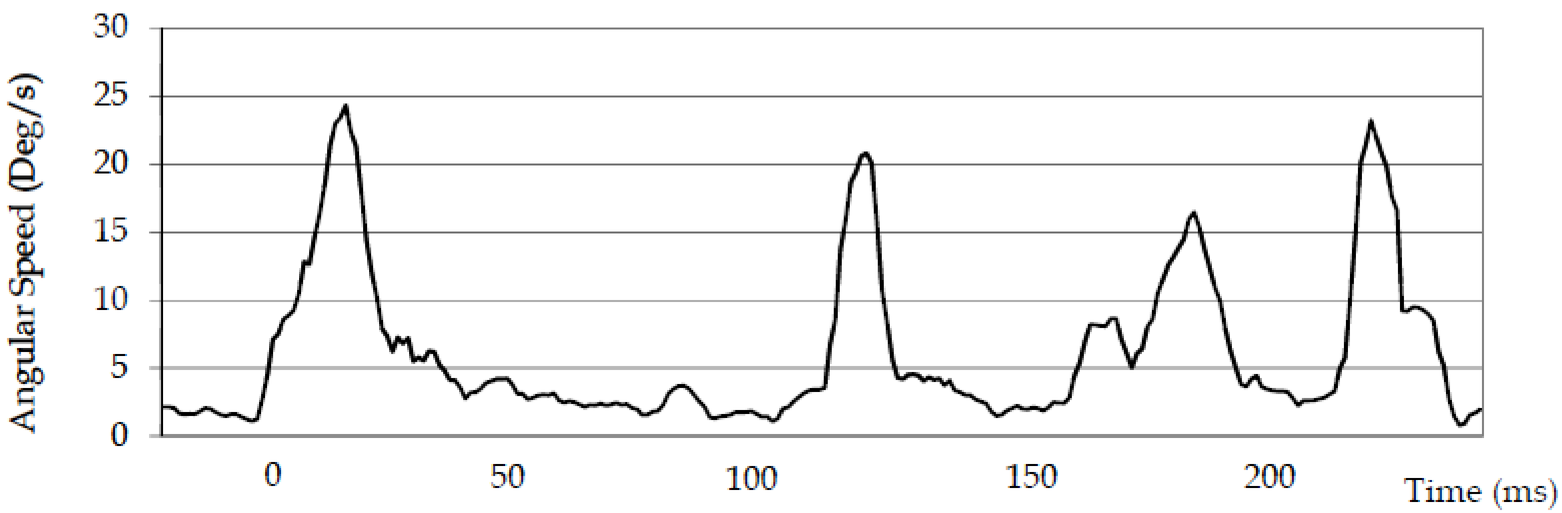


Figure 2.7: *Following the optimized initial impulse model, after the ballistic movement: (a) the target might be selected, (b) under shooted or (c) over shooted. For situations (b) and (c) subsequent corrective movements are required.*

D. E. Meyer, R. A. Abrams, S. Kornblum, C. E. Wright, and J. E. K. Smith. Optimality in Human Motor Performance: Ideal Control of Rapid Aimed Movements. Psychological Review, 95(3):340–370, 1988.

Optimized Initial Impulse Model

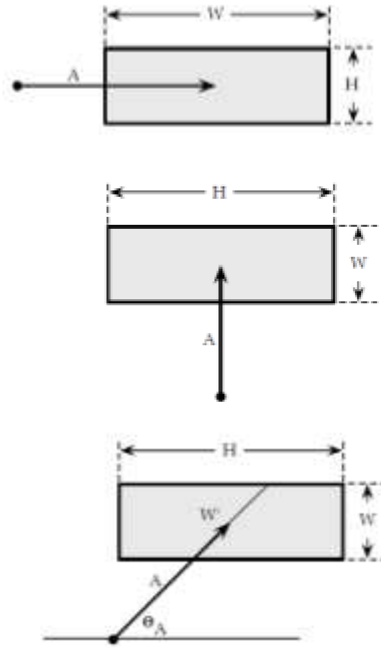
- Acquisition tasks are subdivided in a two-step movement
  - Ballistic phase. A fast and inaccurate movement is made towards the target.
  - Correction phase. If the target is not acquired, iterative slow correction movements are executed until the target is acquired



Example of a velocity profile for a 3D acquisition task using raycasting selection. Ballistic and corrective phases of the movement are clearly visible.

Fitts' law and beyond…

- Extension to 2D motions



$$MT = a + b\log_2\left(\frac{2A}{W}\right) + c\log_2\left(\frac{2A}{H}\right)$$

E. Crossman. The measurement of perceptual load in manual operations. PhD thesis, University of Birmingham, 1956.

$$MT = a + b\log_2\left(\sqrt{\left(\frac{A}{W}\right)^2 + \eta\left(\frac{A}{H}\right)^2} + 1\right)$$

Johnny Accot and Shumin Zhai. Refining Fitts' law models for bivariate pointing. ACM *SIGCHI conference on Human factors in computing systems*, pages 193–200., 2003.

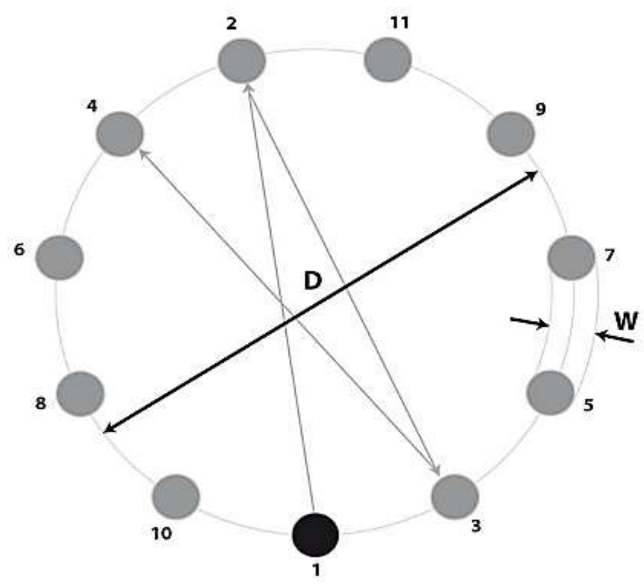
- Extensions to 3D motions

$$ID_{WtEuc\Theta} = \log_2\left(\sqrt{f_W(\Theta)\left(\frac{A}{W}^2\right) + f_H(\Theta)\left(\frac{A}{H}^2\right) + f_D(\Theta)\left(\frac{A}{D}^2\right)} + 1\right)$$

Tovi Grossman and Ravin Balakrishnan. Pointing at trivariate targets in 3D environments. ACM *SIGCHI conference on Human factors in computing systems*, pages 447–454. ACM, 2004.

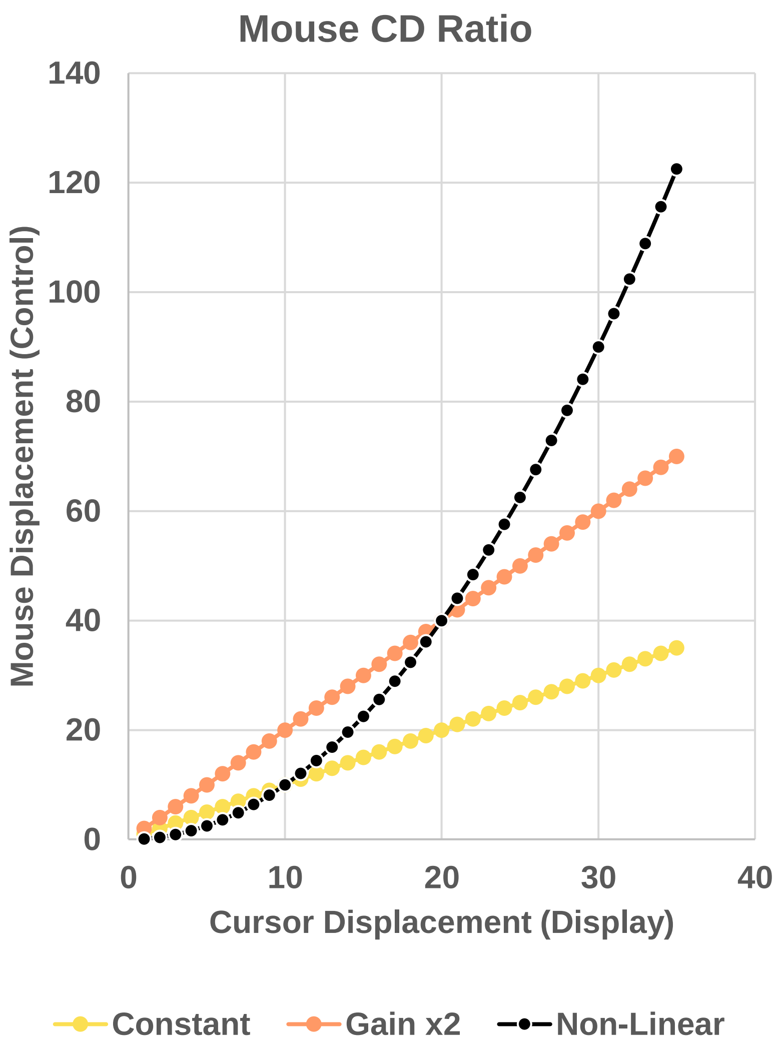
Fitts' Law

- Fitts' law is so well know because it provides one of the few **quantitative measures** for HCI research.
- There **ISO 9241-9** standard which provides a standardized evaluation scenario for testing 2D interactions (e.g. mouse selection).



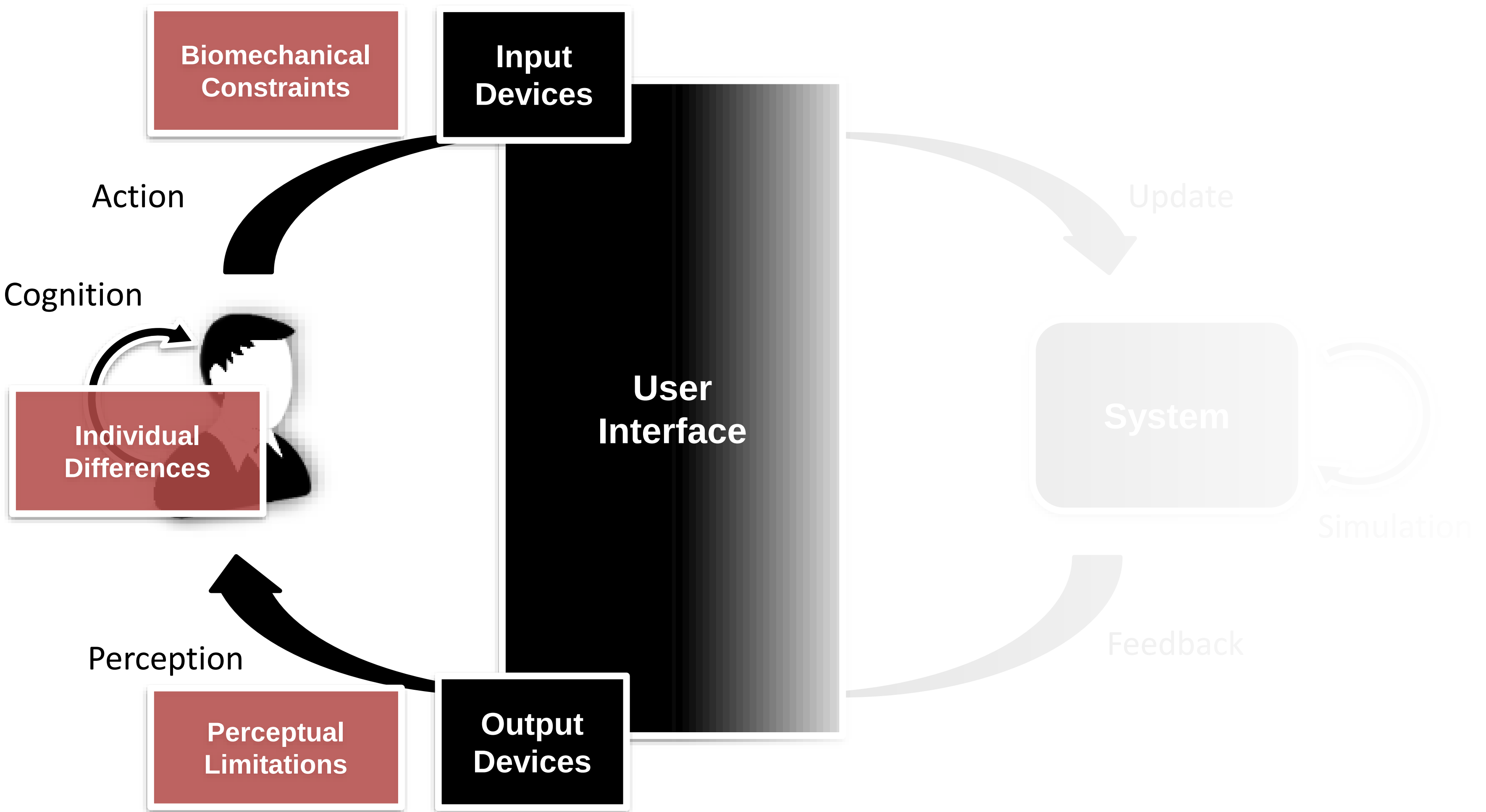
Application of Fitts' Law: Input Mapping

- Function that maps the input DoFs to the DoFs of the interaction tool.
  - Isomorphic Mapping: Ensures that there is a direct mapping between the input DoFs and the DoFs of the tool.
  - Anisomorphic Mapping: Applies a linear or nonlinear transformation to the input data. This function is defined by the Control/Display Ratio.



Wrap-up

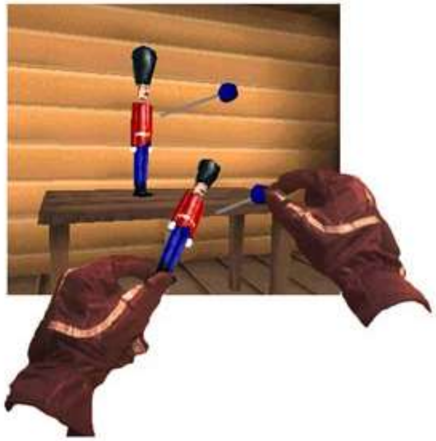
The Interaction Loop



3D Interaction Tasks

- **Basic** 3D Interaction Tasks
  - **Selection**: The user choses a 3D object from a set of objects
  - **Manipulation**: The user applies spatial rigid transformations
  - **Navigation**: The user modifies its virtual position in the environment
  - **Application Control**: The user issues commands to the application

Selection



Manipulation

Navigation