A Review of Current Trends on Visual Perception Studies in Virtual and Augmented Reality

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ABSTRACT

In the development of novel algorithms and techniques in virtual and augmented reality (VR/AR), it is crucial to take human visual perception into account. For example, when hardware resources are a restraining factor, the limitations of the human visual system can be exploited in the creation and evaluation of new effective techniques. Over the last decades, visual perception evaluation studies have become a vital part of the design, development, and evaluation of immersive computer graphics applications. This course aims at introducing the attendees to the basic concepts of visual perception applied to computer graphics and it offers an overview of recent perceptual evaluation studies that have been conducted with head-mounted displays (HMDs) in the context of VR and AR applications. During this course, we call attention to the latest published courses and surveys on visual perception applied to computer graphics and interaction techniques. Through an extensive search in the literature, we have identified six main areas in which recent visual perceptual evaluation studies have been focused on: distance perception, avatar perception, image quality, interaction, motion perception, and cybersickness. Trends, main results, and open challenges are discussed for each area and accompanied with relevant references offering the attendees a wide introduction and perspective on the topic.

CCS CONCEPTS

• **Computing methodologies** → **Perception**; **Virtual reality**; **Mixed / augmented reality**.

KEYWORDS

visual perception, virtual reality, augmented reality, head mounted device

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1 INTRODUCTION

With the increased adoption of *virtual reality* (VR) and *augmented reality* (AR) technologies in several industry areas, e.g. gaming, healthcare, industrial prototyping and training, especially using head-mounted displays (HMDs), it is significantly critical to ensure immersion and high-quality experiences for users of these systems. Using VR HMDs, the user is entirely immersed in the virtual environment (VE), and an important requirement is for the observer to perceive the virtual interaction as a natural experience. Hence, it is vital that the device and applications provide a high visual quality result. AR headsets allow the user to see both the real and digital world simultaneously, adding virtual objects to the view and displaying information on top of what the user is seeing. Hence, it is crucial how virtual objects are perceived regarding spatial location, visual appearance, and visual coherence. With HMDs come challenges regarding maintaining a high visual quality result for the observer. In the last few decades, research in computer graphics has increasingly incorporated knowledge about human visual perception in the design, development, and evaluation of novel technical systems and techniques.

In addition to quantitative metrics, perceptual evaluation studies using human observers are essential to assess the ultimate perceived experience, immersion, and quality. Over the last decades, the development of novel VR and AR technologies, has led to more user experiences which require to be assessed by human observers.

The course provides an overview of recent research literature in the area of VR and AR, focusing on visual perceptual evaluations that have been carried out using HMDs in the last years. For the analysed papers, the research questions and main results are described together with future research directions. Key trends are also highlighted and discussed. The main research areas identified were classified in six categories: *distance perception*, *avatar perception*, *image quality*, *interaction*, *motion perception*, and *cybersickness*.

2 FORMAT AND INTENDED AUDIENCE

Format: Half-day course (3h45m).
Audience: This course is relevant for everyone interested in learning about visual perception studies in VR and AR and who wants an update on recent trends and open challenges in the area. In particular, it could benefit beginners and trained VR/AR designers and developers, as well as graphics and interactions researchers.
Prerequisites: This course has no hard prerequisites. Familiarity with concepts of virtual reality, augmented reality, and head mounted devices will be an advantage.

3 COURSE RATIONALE

The aim of this course is to give an overview of how different aspects of human visual perception have recently been studied and applied in immersive virtual and augmented reality applications. Through an extensive search in recent computer graphics literature, we have identified six main research areas of growing interest: distance perception, avatar perception, image quality, interaction, motion perception, and cybersickness. Throughout the course we highlight the main contributions and key trends for each area, the focus and main results of these studies, and discuss some open challenges. The intention of the course is to offer it to a broad attendee base. Researchers interesting in approaching this field as well as VR/AR developers, at all levels of expertise, will learn the recent research questions in the area and their purpose/relevance for the design of high-quality VR/AR immersive applications. In the first part of the course, we introduce the topic of visual perception in graphics and present the main basic theoretical concepts of visual perception and the human visual system needed to understand the remaining part of the course. The second part consists in an outline of previous courses and state-of-the-art publications in the computer graphics community on the topic. This will offer the attendees a convenient summary of useful sources that can be examined for further reading. With the third and fourth parts, we go deeper into detail and describe the findings and the open questions of each identified area.

4 COURSE SYLLABUS

(1) Introduction and Welcome (Garro) (10 min)
   - Who Are We
   - Course Aim
   - Course Outline
(2) Part I: Basic Concepts of Visual Perception (Sundstedt) (30min)
(3) Part II: Overview of Literature in Perceptually Adaptive Graphics (Sundstedt) (30 min)
(4) Part III: Recent Trends and Challenges in Distance Perception, Avatar Perception, and Image Quality (Garro) (60 min)
   - Distance Perception
   - Avatar Perception
   - Image Quality
(5) BREAK (15 min)
(6) Part IV: Recent Trends and Challenges in Interaction, Motion Perception, Cybersickness (Navarro) (60 min)
   - Interaction
   - Motion Perception
   - Cybersickness
(7) Conclusion (Garro) (5 min)
(8) Discussion and Q&A (All) (15 min)

5 COURSE OUTLINE

Throughout the course, around 100 references will be cited presenting the main trends and research focuses. The course will start with an introductory session describing the aim of the course and the learning outcomes. The outline of the course will be also presented. Moreover, we will introduce the six main areas that we have identified through a literature review: distance perception, avatar perception, image quality, interaction, motion perception, and cybersickness. The adopted selection strategy will be also described.

5.1 Part I: Basic Concepts of Visual Perception

Since the course is designed as introductory level, the first part of the course aims at providing a common ground of terminology and basic concepts related to visual perception, e.g. a description of the human visual system, the concept of visual cues and 3D visual perception.

5.2 Part II: Overview of Literature in Perceptually Adaptive Graphics

In this part, the course offers a set of key references summarising the previous courses and surveys regarding visual perception studies and their applications in computer graphics in general as well as specifically in VR and AR domains.

5.3 Part III: Recent Trends and Challenges in Distance Perception, Avatar Perception, and Image Quality

With Part III, we describe more in detail what recently have been studied in the first three areas: distance perception, avatar perception, and image quality.

Distance Perception. We introduce the concept of egocentric distance underestimation [44] in VR environments analysing several aspects which influence this phenomenon. The recent availability of consumer HMDs has led to several works which compared technical factors of different type of devices, e.g. weight, field of view (FOV), and resolution [8, 20, 57]. Other aspects that have been recently studied are the effect of visual stimulation in the far peripheral region of the FOV [16, 29, 30], the influence of the presence of avatars, [5, 6, 12, 17, 18, 31] and the impact of interaction in the virtual environment, e.g. walking or reaching interaction [19, 21, 22, 25, 45]. Distance perception plays a crucial role also in AR, where virtual objects appear in the same space of physical objects. The location of virtual objects in the real world should be perceived accurately to guarantee an effective experience for the observer. We will discuss some of the works which analysed the impact of different visual effects [10, 26, 42, 47].

Avatar Perception. Several recent studies investigated the impact of the presence and different visual characteristics of 3D virtual characters, in particular, self-avatars, on the user experience in VR and AR applications (mostly VR), both in case of synchronous tracking and in case of visuomotor conflicts. Examples of topics that will be discussed for this area are: the influence of the presence of avatars[5], the level of visibility of avatar (e.g. partial avatar, full body avatar) [34, 48], the personalisation of avatar [18, 52], and the level of realism [4, 28, 32], on the following aspects of the immersive experience: spatial perception, body ownership, sense of agency, and sense of presence.

Image Quality. With the integration of eye tracking in HMDs, it has become possible to exploit information from the user in the design of novel algorithms and techniques, e.g. foveated rendering. Different aspects of the rendering pipeline have been modified to incorporate gaze information in HMDs to provide speedups while maintaining a high or improved perceptual quality result, e.g. [41, 46, 53, 54]. Other rendering techniques exploiting the human visual system are based on contrast enhancement [59] and binocular disparity [13]. Other studies in the area of image quality and foveated rendering have focused on computational optics [37], as well as rendering of pre-corrected images [56].

Recently, research interest has also been growing on quality assessment of model-based virtual environments both in VR [39, 58] and AR [1, 2].

5.4 Part IV: Recent Trends and Challenges in Interaction, Motion Perception, and Cybersickness

With Part IV, we continue the detailed description of the main recent works in the other identified areas: interaction, motion perception, and cybersickness.

Interaction. The interaction section presents a set of works that have analysed how 3D object manipulation can be carried out in VE. The section explains how the visual perception system can be used to improve the interactive experience, and how perception studies differ from those in the area of human-computer interaction (HCI). The section divides the works into two clusters: *haptics* analyses techniques to explore the VE through a simulated tactile techniques [11, 33, 50], while *efficiency* studies evaluated the accuracy and overall functionality of the proposed interaction techniques [14, 24].

Motion Perception. The studies included in the motion section analysed how the visual perception system was used in different techniques to navigate through VE, focusing on variables like perceived speed, position and direction. Two major clusters were used to classify the works exposed in the motion section: *Locomotion* reviews the techniques used to aid the process of navigation through the VE [7, 15, 27, 35], and *spatial awareness* evaluated the sense of orientation participants had of the real world, while immersed in the VE [9, 40, 49, 55].

Cybersickness. The cybersickness section reviews studies that explored the undesired motion sickness condition that is perceived when experiencing self-movement in VE. The section introduces the symptoms, potential causes, and some of the mitigation approaches that have been proposed to address cybersickenss. There were two clusters used to categorise the works in the area of cybersickness: *diagnosis* included works that focused on identifying and assessing cybersickness in participants [23, 36, 43], while *stimuli categorisation* exposes studies that evaluated the effects of different visualisation techniques in inducing cybersickness [3, 36, 38, 51].

5.5 Conclusion

To conclude the course, before the discussion, we will offer a brief wrap-up session to summarise the content of the course.

5.6 Discussion

The final part of the course is a Discussion and Q&A session in which we plan to have the attendees to participate in the discussion with interactive tools to acquire real-time feedback. The information collected during the Discussion session will be aggregated and reported in a web page that we are planning to create as to support this course.

6 LECTURERS

The course will be delivered by the following lecturers:

Valeria Garro: Associate Senior Lecturer at the Department of Computer Science at Blekinge Institute of Technology working on the ViaTecH Synergy research project "Human-centered computing for novel visual and interactive applications". Previously, she worked as research fellow at Visual Computing Lab (ISTI-CNR, Italy) and as a postdoc at University of Verona, Italy, focusing on 3D reconstruction and 3D shape analysis. She obtained her Ph.D. degree in Computer Science in 2013 at the University of Verona specialising in computer vision. Her current research interests are human-centred computing, visual perception applied to 3D shape analysis and computer vision.

Veronica Sundstedt: Associate Professor and Head of Department of Computer Science at Blekinge Institute of Technology. Her research focuses on visual and interactive computing, particularly on computer graphics, novel human-computer interaction techniques and visual perception. She has a M.Sc. in Media Technology, University of Linköping, and a Ph.D. in Computer Science (Computer Graphics) from the University of Bristol. She has been a Lecturer at Trinity College Dublin and as postdoc at the University of Bristol and the University of Bath. She is currently the project owner for the ViaTecH Synergy research project.

Diego Navarro: Ph.D. student in Computer Science, associated with the ViaTecH Synergy research project "Human-centered computing for novel visual and interactive applications", at Blekinge Institute of Technology. Diego's research interests are human-computer interaction, emerging interaction technologies, virtual reality, artificial intelligence and psychophysiological feedback. Diego holds a Bachelor degree on Multimedia Engineering from Nueva Granada Military University (2009), and a Master of Science degree on Design, Interaction and Game Technologies from Blekinge Institute of Technology (2014).

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SIGGRAPH ASIA 2020
VIRTUAL

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INTRODUCTION & WELCOME

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Who Are We

Valeria Garro
Associate Senior Lecturer at Blekinge Institute of Technology (BTH), Sweden
Interests: human-centered computing, visual perception, 3D shape analysis, computer vision, VR, and AR.

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Diego Navarro
PhD student at Blekinge Institute of Technology (BTH), Sweden
Interests: human-computer interaction, emerging interaction technologies, virtual reality, artificial intelligence, and psychophysiological feedback.

Course Aim

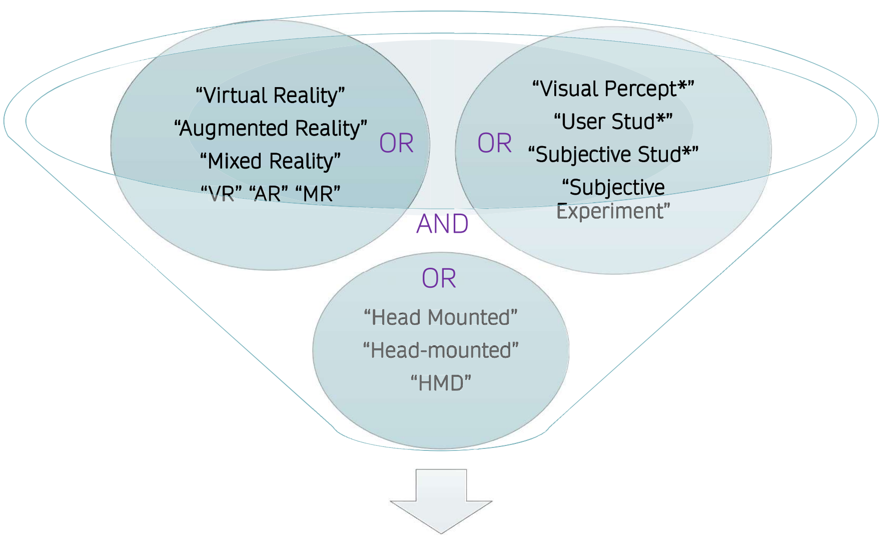
- Introduction to human visual perception.
- How have different visual perception aspects been studied and applied in VR and AR?
- Summary of recent literature on the topic.
- Main research trends, challenges and open questions in six different areas.

Visual Perception in VR and AR

- Visual perception is a broad topic.
- Several characteristics and parameters have been investigated and applied on different areas.

Fig. 2-I. Image by Free-Photos from Pixabay. Pixabay License.
https://pixabay.com/photos/milky-way-universe-person-stars-1023340/

Literature Selection Strategy



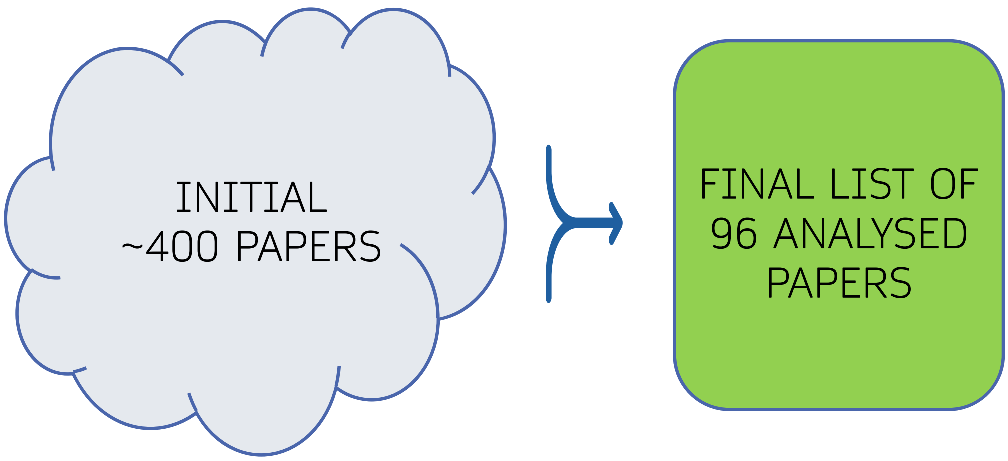
~ 400 Papers

- Search on Scopus.
- Time limit: Publication Year > 2012
- Focus on “visual perception” (sound, haptic have been excluded).
- Posters and short papers excluded.

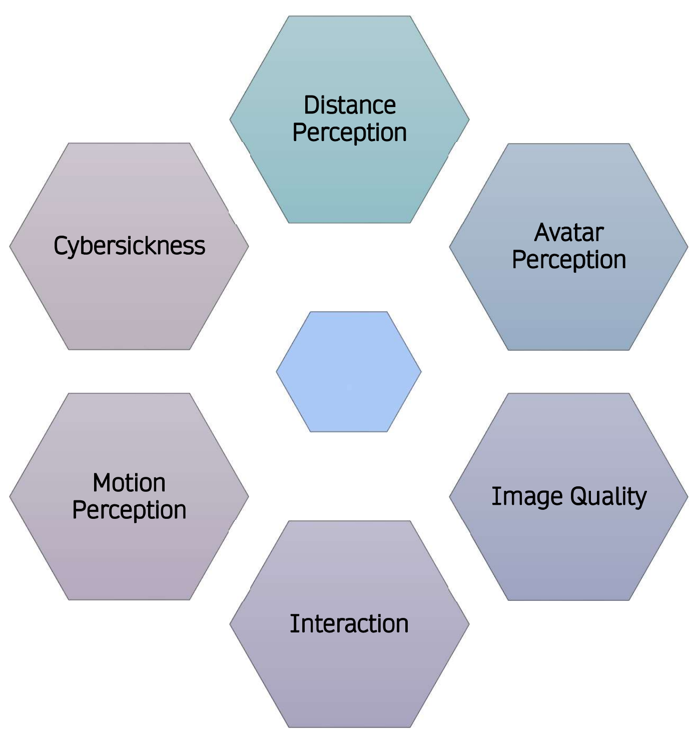
- Focus on the impact of visual perception properties and visual elements on VR/AR HMD applications.

> 1000 if we use “percept*” instead of “visual percept*”

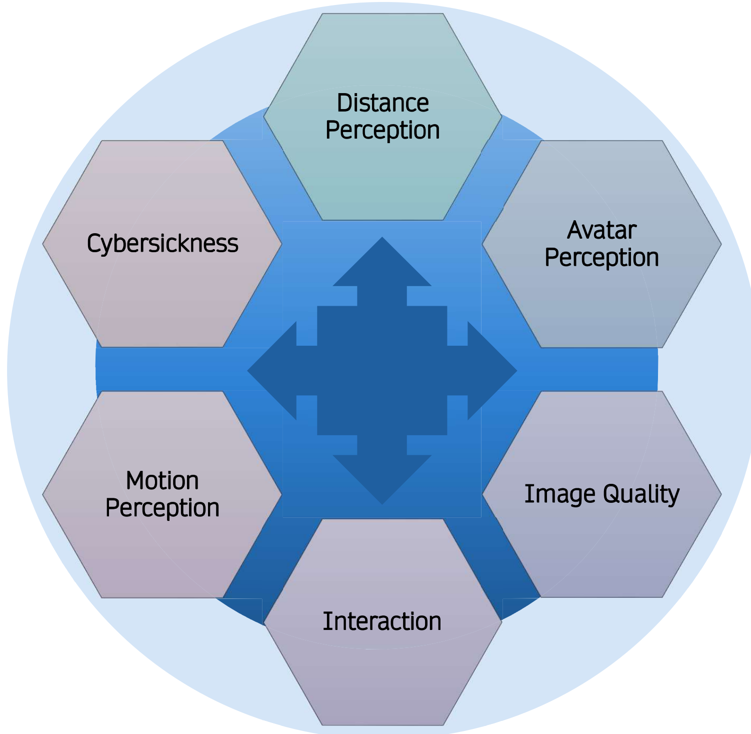
Literature Selection Strategy



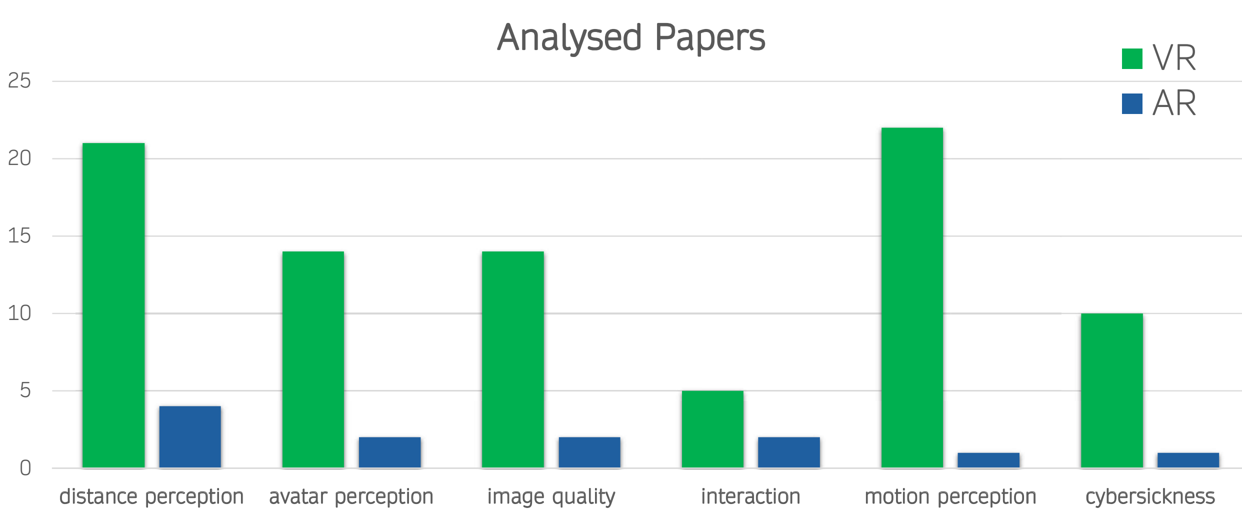
Identified Areas



Identified Areas



Identified Areas



Course Structure

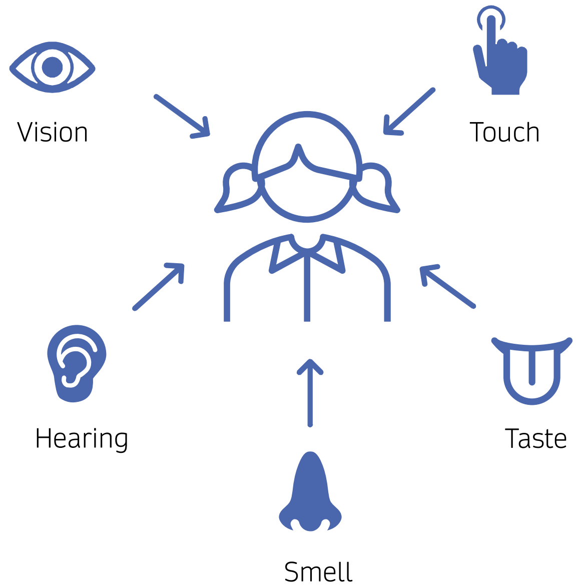
- **Introduction & Welcome** (Garro) (10 min)
- **Part I:** Basic Concepts of Visual Perception (Sundstedt) (30min)
- **Part II:** Overview of Literature in Perceptually Adaptive Graphics (Sundstedt) (30 min)
- **Part III:** Recent Trends and Challenges in Distance Perception, Avatar Perception, and Image Quality (Garro) (60 min)
  - Distance Perception
  - Avatar Perception
  - Image Quality
- **BREAK** (15 min)
- **Part IV:** Recent Trends and Challenges in Interaction, Motion Perception, and Cybersickness (Navarro) (60 min)
  - Interaction
  - Motion Perception
  - Cybersickness
- **Conclusion** (Garro) (5 min)
- **Discussion and Q&A** (All) (15 min)

PART I

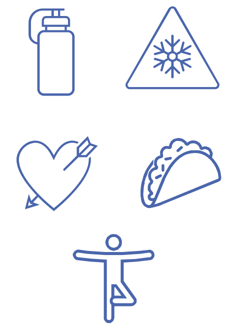
BASIC CONCEPTS OF VISUAL PERCEPTION

Veronica Sundstedt
Blekinge Institute of Technology

Perception and our Senses



There are also other examples...



What is Visual Perception?

- Our ability to acquire and interpret information from the environment by processing light in the visible spectrum through the eye

Fig. 1-PI.

Fig. 1-PI. Image by Peggy und Marco Lachmann-Anke from Pixabay. Pixabay License.
https://pixabay.com/illustrations/binoculars-search-see-to-find-1026423/

Visible Light Spectrum

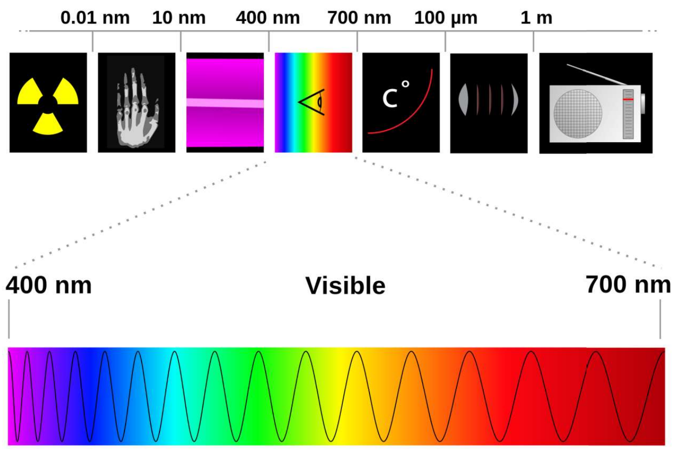


Fig. 2-PI. User: Tatoute / Creative Commons Attribution-Share Alike 3.0 Unported license. (https://commons.wikimedia.org/wiki/File:Spectre_visible_light.svg).

The Human Eye

- Cornea
- Pupil
- Lens
- Retina
- Fovea
- Optic nerve

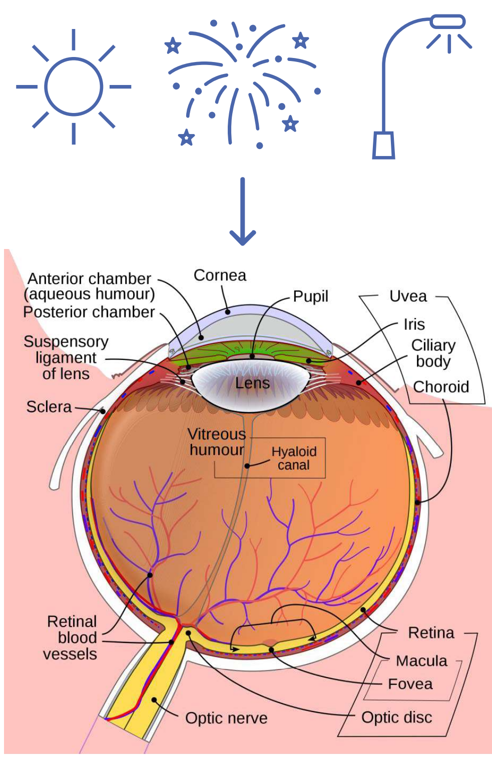


Fig. 3-PI. Image by Rhcastilhos. And Jmarchn. Creative Commons Attribution-Share Alike 3.0 Unported license. https://commons.wikimedia.org/wiki/File:Schematic_diagram_of_the_human_eye_en.svg

Human Visual System

- The eyes
- The optic nerves
- The brain

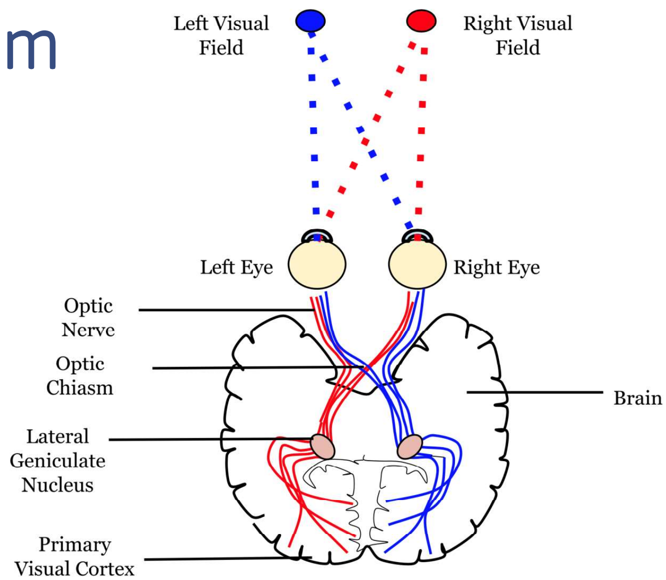


Fig. 4-PI. Mads00 / CC BY-SA (https://creativecommons.org/licenses/by-sa/4.0) https://commons.wikimedia.org/wiki/File:Neural_pathway_diagram.svg

Photoreceptors (Rods and Cones)

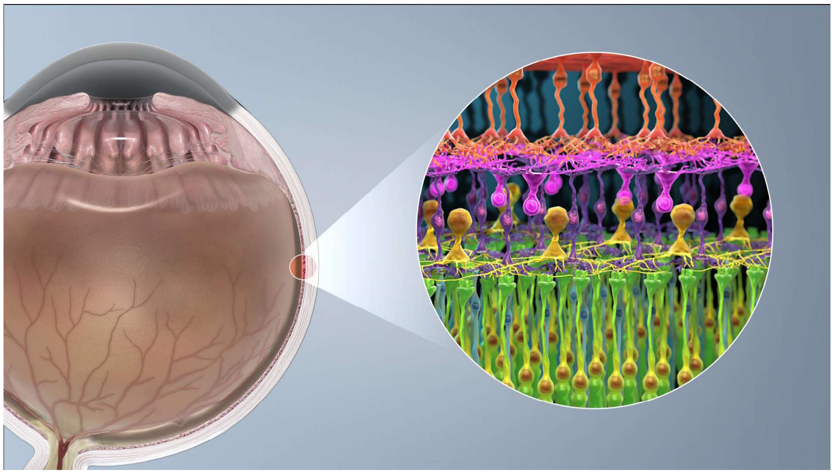


Fig. 5-PI. Image by https://www.scientificanimations.com/wiki-images/. Creative Commons "BY-SA (Attribution-ShareAlike 4.0 International)"

Visual Acuity and Photoreceptor Distribution

- Visual acuity is the resolution limit of the eye and our ability to see fine details (Snowden et al. 2006)
- Uneven distribution of cells in the retina
- Foveal vision has the highest visual acuity (area of about 2°)
- Eye movements to move the image to this area

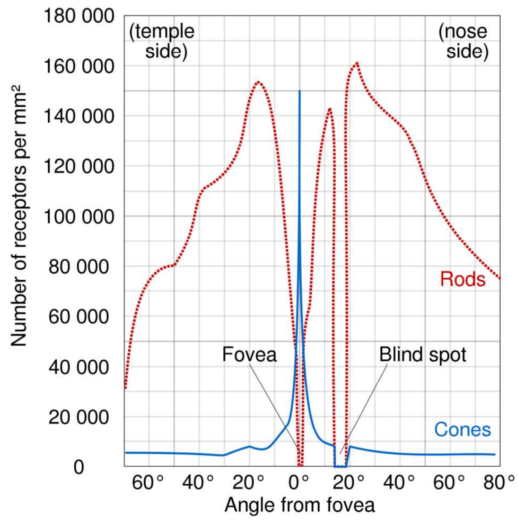


Fig. 6-PI. Author: Cmglee. Creative Commons Attribution-Share Alike 3.0 Unported license. https://commons.wikimedia.org/wiki/File:Human_photoreceptor_distribution.svg

Visual Acuity Test

- "Visual angle of thumb's width is about 2 deg" (O'Shea 1991)
- Highest visual acuity maps to a visual angle of about twice as large as the thumb when the arm is stretched out (Thompson et al. 2011)

Fig. 7-PI. Image by Peggy und Marco Lachmann-Anke from Pixabay. Pixabay License. https://pixabay.com/illustrations/thumbs-up-gut-thumb-high-finger-1026395/

Central and Peripheral Vision

- Field of view (Thompson et al. 2011)
  - 200° horizontal, 135° vertical
  - Overlap 120°

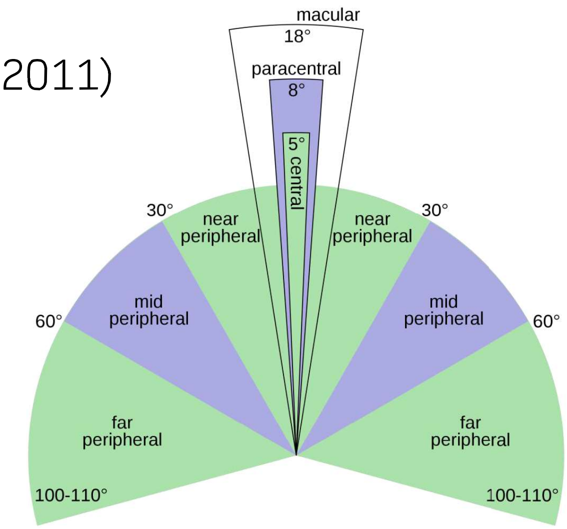


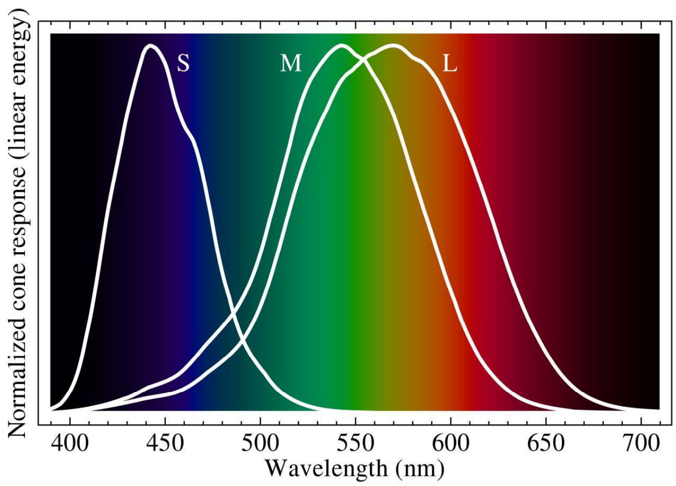
Fig. 8-PI. Author: Zyxwv99. Creative Commons Attribution-Share Alike 4.0 International license. https://commons.wikimedia.org/wiki/File:Peripheral_vision.svg

Colour Perception

- Young-Helmholz theory - Trichromatic theory
- Three kinds of cones sensitive to red, green, and blue

Fig. 9-PI. Image by PublicDomainPictures from Pixabay. Pixabay License. https://pixabay.com/photos/abstract-red-green-blue-primary-19141/

Spectral Absorption Curves

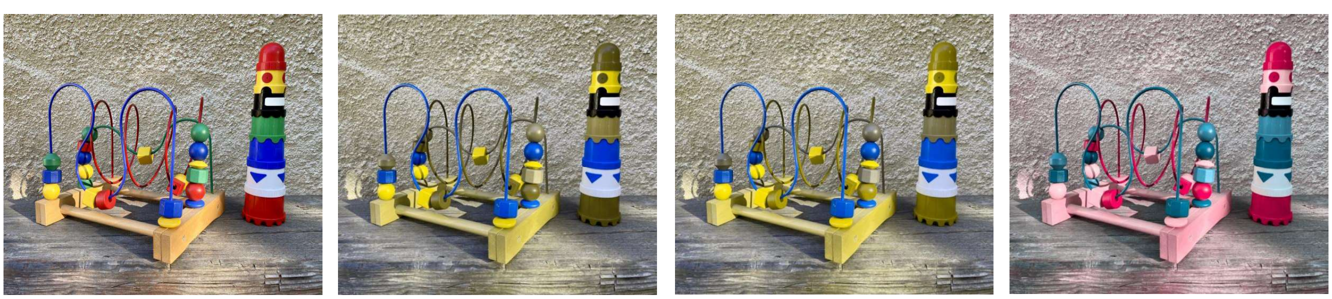


Short (S)
Medium (M)
Long (L)

Fig. 10-PI. Image by BenRG. Creative Commons Public Domain. https://commons.wikimedia.org/wiki/File:Cone-fundamentals-with-srgb-spectrum.svg

Colour Blindness

- 1/12 men (8%), 1/200 women (0.5%) (https://www.colourblindawareness.org/colour-blindness/)
- Total or partial (most common red/green, blue/yellow)



Normal vision

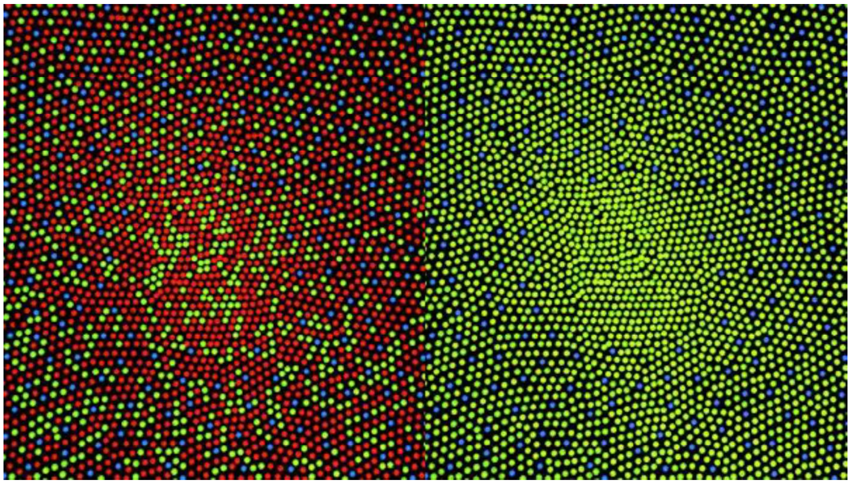
Protanopia (red blind)

Deuteranopia (green blind)

Tritanopia (blue blind)

Distribution of Cone Cells in the Fovea

Normal vision



Protanopia
(red blind)

Fig. 11-PI. Attribution: Mark Fairchild. Creative Commons Attribute-Share Alike 3.0 Unported License. https://commons.wikimedia.org/wiki/File:ConeMosaics.jpg

Contrast Sensitivity

Fig. 12-PI. Author: Aleksey463. Creative Commons. Public Domain. https://commons.wikimedia.org/wiki/File:SinVibr.png

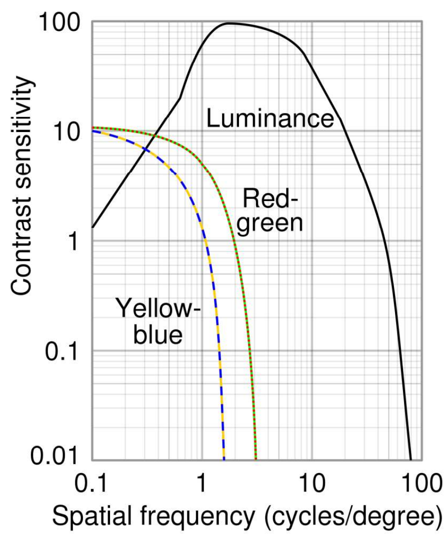
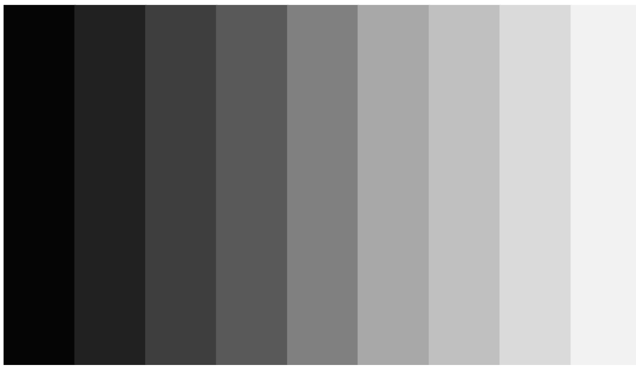


Fig. 13-PI. Author: Cmglee. Creative Commons Attribution-Share Alike 4.0 International license. https://commons.wikimedia.org/w/index.php?curid=90524055

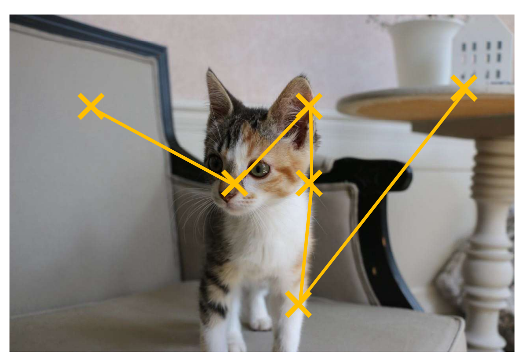
Brightness Perception

- Mach Band effect



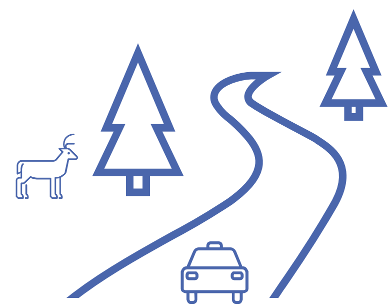
Eye Movements

- Eyes move 3-4 times / sec (Snowden et al. 2006)
- Different types (Duchowski 2017, Duchowski 2018)
  - Fixations (tremors, drifts, microsaccades)
  - Saccades (fast)
  - Smooth pursuits
  - Vergence (accommodation)
  - Vestibulo-ocular reflex
- Scan paths
  - Sequence of fixations forming a path



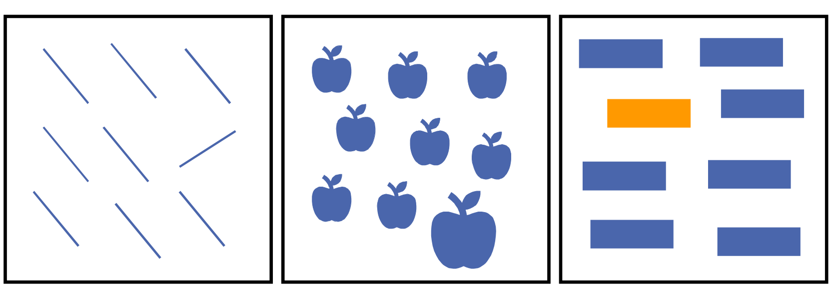
Human Visual Attention

- Visual attention helps us select relevant information
- Bottom-up processing (Itti et al. 1998)
  - Attracts our attention automatically (saliency)
  - Movement, orientation, intensity, colour
- Top-down processing (Yarbus 1967)
  - Task-driven (driving a car, playing a game)



Saliency (Bottom-Up)

- Low-level features attracting attention (orientation, size, colour, intensity, motion, etc.)

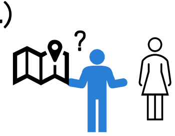


Orientation | Size | Colour

Selective Attention

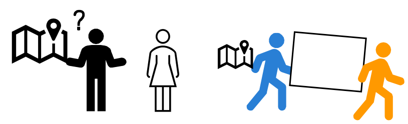
- Inattentional blindness - if you focus actively on a thing you might fail to notice other things (Mack and Rock, 1998)
  - Simons and Chabris (1999) - Invisible gorilla test, count basketball passes, ca 50% failed to notice it
- Change blindness – when you fail to notice a change (https://www.youtube.com/watch?v=VkrrVozZR2c)

1.)

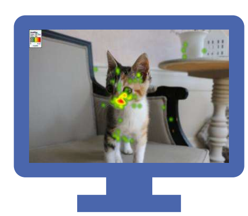


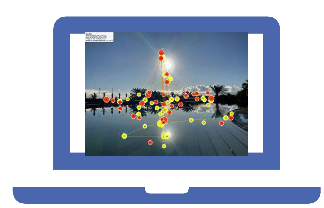
2.)

3.)



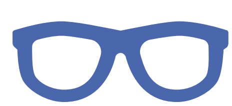
Eye Tracking

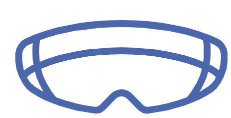




What is visually important?

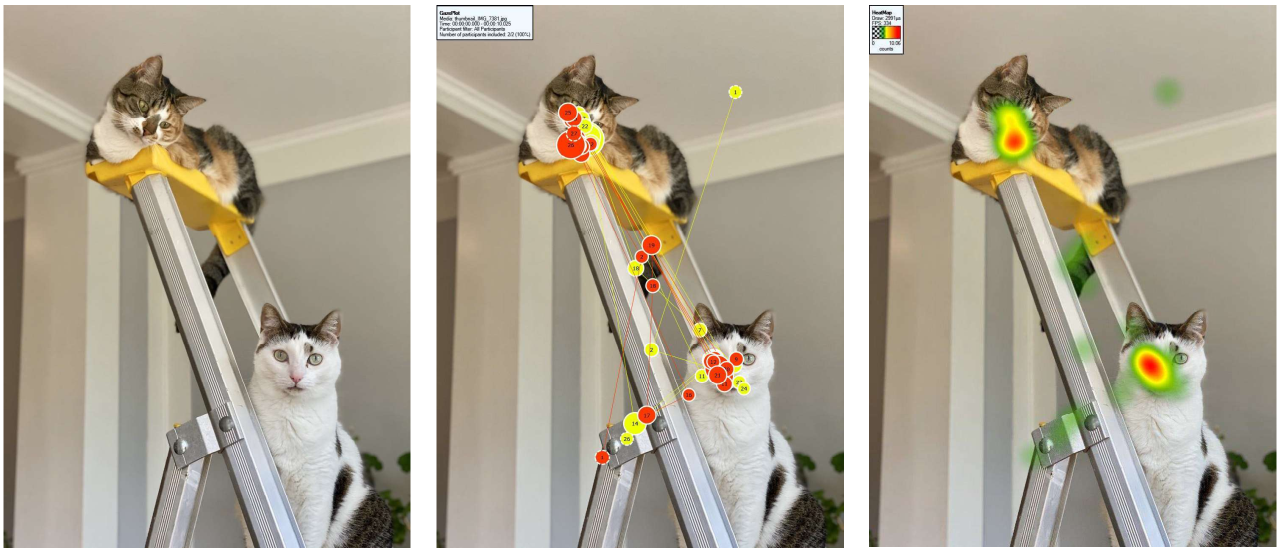
- Eye tracking is technology (and software) allows you to record an observer's eye movements (needs calibration)
  - Video-based, mechanical, electronic
- Portable device, screen, laptop, glasses
- Recently incorporated in head-mounted displays (HMDs)
  - Gaze analysis in VR
  - Gaze interaction in VR





Example data: fixations, saccades, blinks, etc.
For more information see (Duchowski 2020).

Scan Path and Heat Map Visualisation

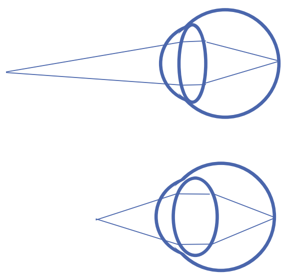


Depth Perception (Monocular or Binocular)

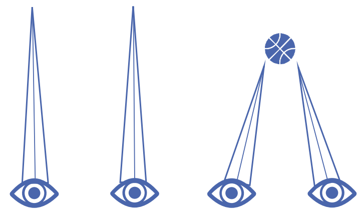
3D View-Master (binocular depth perception).

Depth Perception (Non-Pictorial Cues)

Accomodation (focus)



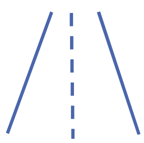
Vergence (div./conv.)



Binocular disparity (stereopsis)
- Different views from each eye

Depth Perception (Pictorial Cues)

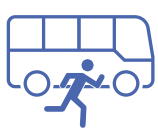
Linear perspective



Texture gradient

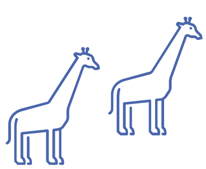
Fig. 14-PI.

Overlap/occlusion/ interposition



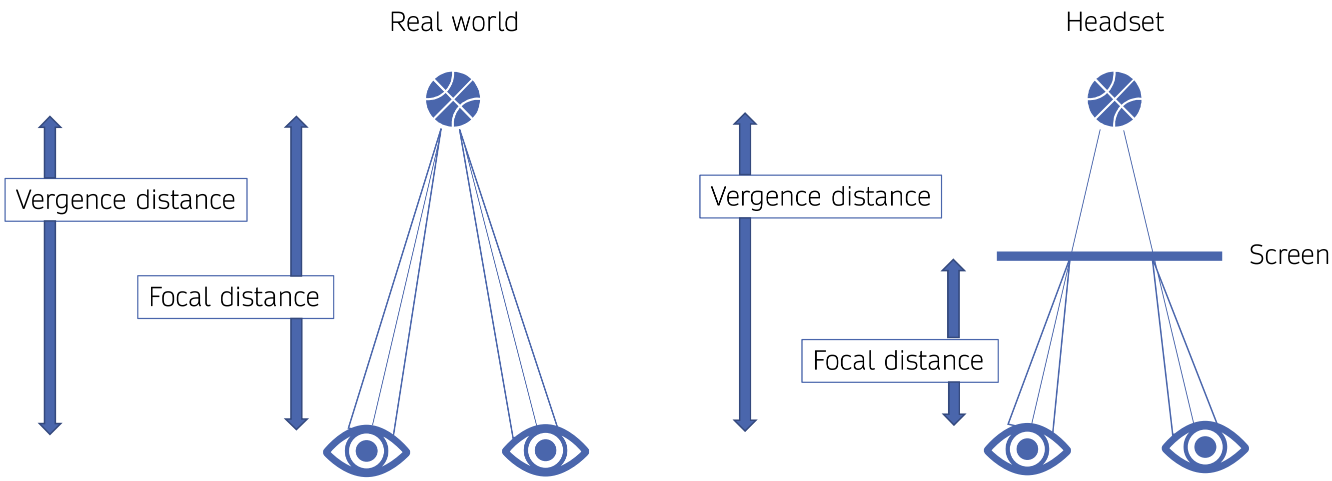
Relative size/ familiar size

Relative height in visual field



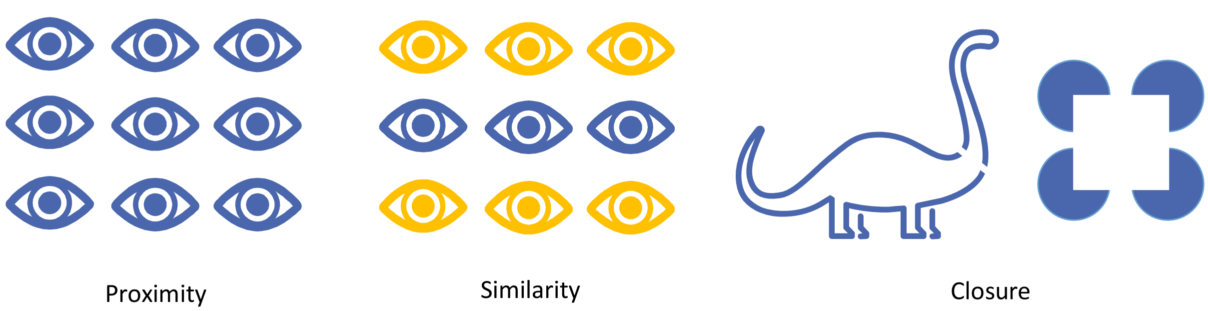
Other cues: shadows, atmosphere, motion, etc.

Vergence and Accommodation Conflict

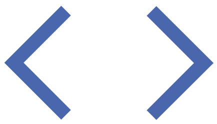


Adapted from: https://agilitypr.news/AR,-VR,-MR,-What-Can-Be-Improved-9444

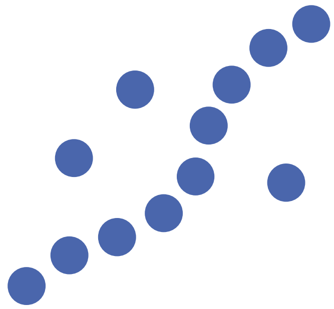
Gestalt Psychology - Gestalt Laws



Gestalt Psychology - Gestalt Laws



Symmetry



Continuity

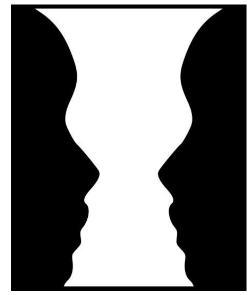


Figure and Ground

Fig. 15-PI. Author: Bryan Derksen.
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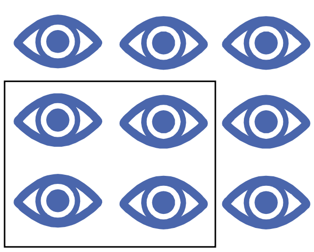
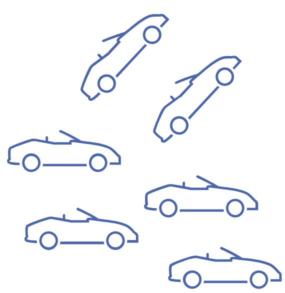
https://commons.wikimedia.org/wiki/File:Cup_or_faces_paradox.svg

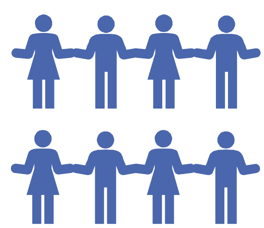
Gestalt Psychology - Gestalt Laws



Common Region



Common Faith



Connection

Visual Perception in Graphics (AR/VR)

- Gaze-based interaction
- Attention-based level of detail
- Foveated rendering (selective rendering)
- Artificial intelligence in games
- Attentive displays / intelligent user interfaces
- Redirected walking locomotion

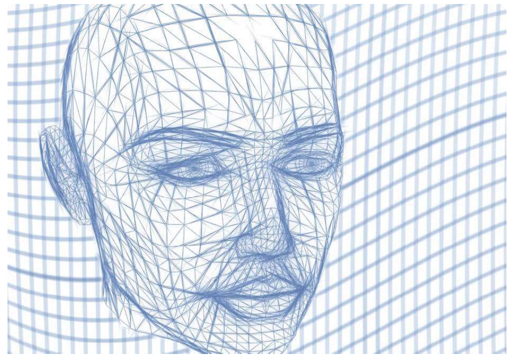


Fig. 16-PI. Image by Gerd Altmann from Pixabay. Pixabay License.
https://pixabay.com/illustrations/head-wireframe-face-lines-web-663997/

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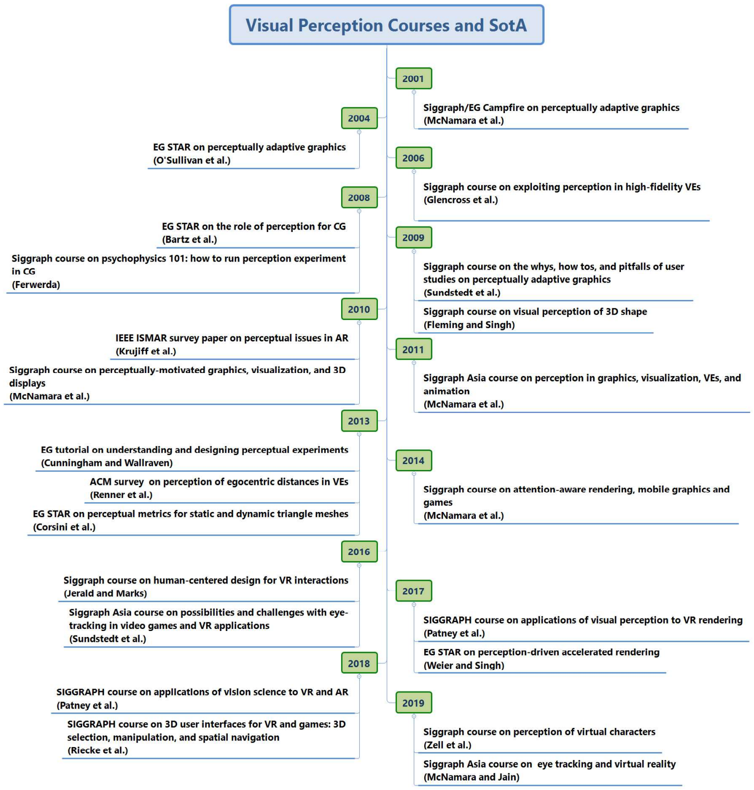
PART II

OVERVIEW OF LITERATURE IN PERCEPTUALLY ADAPTIVE GRAPHICS

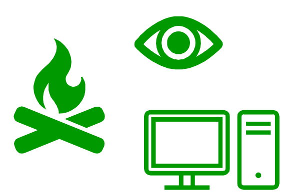
Veronica Sundstedt
Blekinge Institute of Technology

Timeline of Visual Perception Courses and Survey Presented in the CG Community



- Visual perception in computer graphics, the early years.
- How to run user studies?
- Perception in AR
- Perception in computer graphics and visualization
- Perception applied to rendering
- Eye tracking and VR
- Interaction in VR
- Perception of virtual characters

Early Years

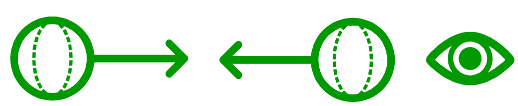


Siggraph/EG Campfire on perceptually adaptive graphics

McNamara et al. (2001)

- Interdisciplinary meeting
- Discuss how to exploit human visual perception in computer graphics
- Areas: *interactive graphics*, *image fidelity*, *distance and scale in computer graphics*, *scene perception*, *visualisation*, and *applications* in computer graphics.

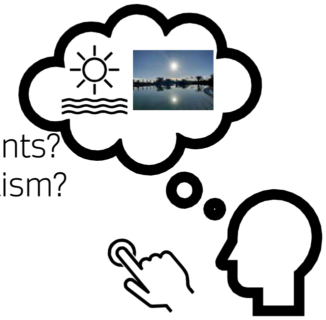
EG STAR on perceptually adaptive graphics



O'Sullivan et al. (2004)

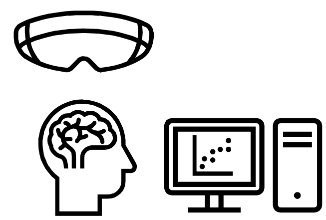
- Areas: *interactive graphics*, *image fidelity*, *animation and virtual environments (VEs)*, and *visualisation and non-photorealistic rendering (NPR)*.

Siggraph course on exploiting perception in high-fidelity VEs
Glencross et al. (2006)



- What to consider when creating high-fidelity virtual environments?
- How can human visual perception be exploited to achieve realism?
- Perceptually-driven real-time rendering.
- Physically-based simulations.
- Intuitive interactions.

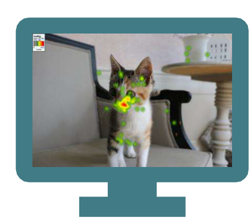
EG STAR on the role of perception for CG
Bartz et al. (2008)



- VR
- Rendering and animation
- Visualisation
- Fundamental of psychophysics

How to Run User Studies?

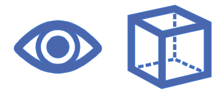
Siggraph course on psychophysics 101: how to run perception experiment in CG
Ferwerda (2008)



Siggraph course on the whys, how tos, and pitfalls of user studies on perceptually adaptive graphics
Sundstedt et al. (2009)

EG tutorial on understanding and designing perceptual experiments
Cunningham et al. (2013)

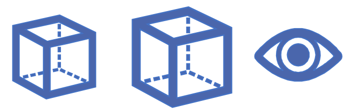
Siggraph course on visual perception of 3D shape
Fleming and Singh (2009)



- Estimation of 3D shapes from 2D images.
- Improve phororealistic and non-photorealistic rendering leveraging on knowledge about human visual system.

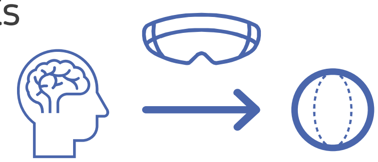
EG STAR on perceptual metrics for static and dynamic triangle meshes
Corsini et al. (2013)

- Perception-correlated metrics for comparing 3D meshes.



ACM survey on perception of egocentric distances in VEs
Renner et al. (2013)

- Review of recent user studies evaluating the topic.
- Underestimation of egocentric distances in VR.



Perception in AR

IEEE ISMAR survey paper on perceptual issues in AR
Kruijff et al. (2010)

- Classification of perceptual issues in AR in five categories:

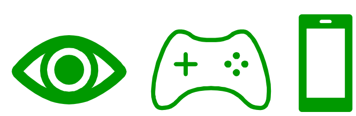
- Environment: e.g. structure, colors, env. conditions
- Capturing: e.g. lens issues, color correctness
- Augmentation: e.g. occlusion, layer interferences
- Display device: e.g. stereoscopy, latency, field of view
- Individual user differences: e.g. depth perception cues, accomodation

Perception in Graphics and Visualization

- Siggraph course on perceptually-motivated graphics, visualization, and 3D displays
  McNamara et al. (2010)
  - Optimise rendering.
  - Improve design and presentation in 3D stereoscopic display media.
  - Create improved large data visualisations.

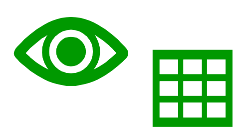
- Siggraph Asia course on perception in graphics, visualization, VEs, and animation
  McNamara et al. (2011)
  - Visual attention and visual memory.
  - Highlight previous work done in perceptually motivated rendering, interactive graphics, animation, and VEs.

Perception in Rendering



- Siggraph course on attention-aware rendering, mobile graphics and games
  McNamara et al. (2014)
  - How visual attention models can be applied in mobile rendering and games for optimisation purposes.
  - Visual saliency
  - Level of Detail

- EG STAR on perception-driven accelerated rendering
  Weier and Singh (2017)
  - Optimisation applying visual attention models.
  - Possibilities of eye-tracking technology.



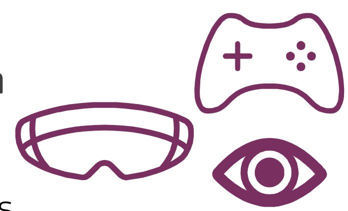
Perception in Rendering

- SIGGRAPH course on applications of visual perception to VR rendering
  Patney et al. (2017)

- SIGGRAPH course on applications of vision science to VR and AR
  Patney et al. (2018)

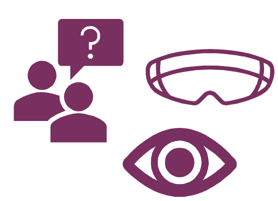
  - Fundamentals of visual perception Possibilities of eye-tracking technology.
  - Case Studies:
    - Redirected walking locomotion techniques.
    - ChromaBlur rendering to improve accommodation and realism.
    - Accommodation-invariant computational near-eye displays.

Eye-Tracking and VR



- Siggraph Asia course on possibilities and challenges with eye-tracking in video games and VR applications
  Sundstedt et al. (2016)
  - Review of eye-tracking in video games and VR applications.
  - Possibilities and challenges with gaze-based interaction.
  - Lessons learned from developing a video game application using eye-tracking.

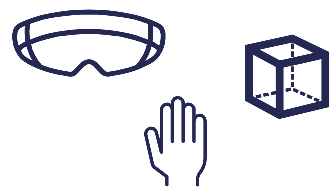
- Siggraph Asia course on eye tracking and virtual reality
  McNamara and Jain (2019)
  - Eye-tracking to improve user experiences and usability in VR.



Interaction in VR

- Siggraph course on human-centered design for VR interactions
  Jerald and Marks (2016)
  - Intuitive interactions in VR environments, games.
  - Avoid user's discomfort and side effects e.g. tiredness, sickness.

- SIGGRAPH course on 3D user interfaces for VR and games: 3D selection, manipulation, and spatial navigation
  Riecke et al. (2018)
  - 3DUIs design.
  - Selection and manipulation of 3D objects.
  - How to spatially navigate these interfaces.



Perception of Virtual Character

- Siggraph course on perception of virtual characters
  Zell et al. (2019)
  - Overview of perceptual studies on virtual characters.
  - Low-level cues (e.g. facial proportions, shading, level of detail)
  - High-level cues (e.g. behavior or artistic stylization)

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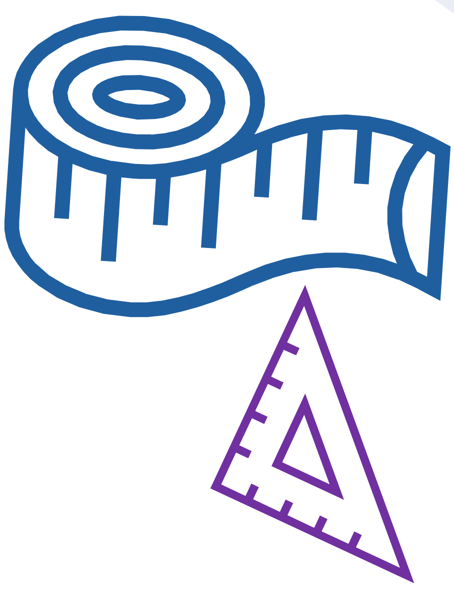
PART III

RECENT TRENDS AND CHALLENGES IN DISTANCE PERCEPTION, AVATAR PERCEPTION, AND IMAGE QUALITY

Valeria Garro
Blekinge Institute of Technology



DISTANCE PERCEPTION

Distance Perception in VR

- Do we perceive distance differently in virtual environments (VEs) ?
- Egocentric distance underestimation in VR, of about 74% of the actual distances (Renner et al. 2013)

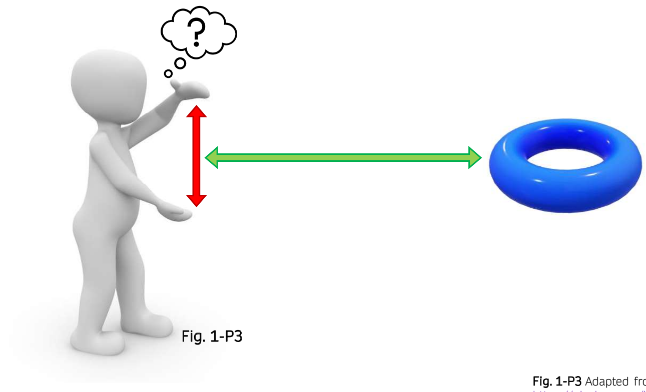


Fig. 1-P3

Egocentric Distance Underestimation

- What might be the factors contributing to this phenomenon?
- (Renner et al. 2013) 4 groups:
  - Technical factors
  - Compositional factors
  - Human factors
  - Measurement methods

Technical and Compositional Factors

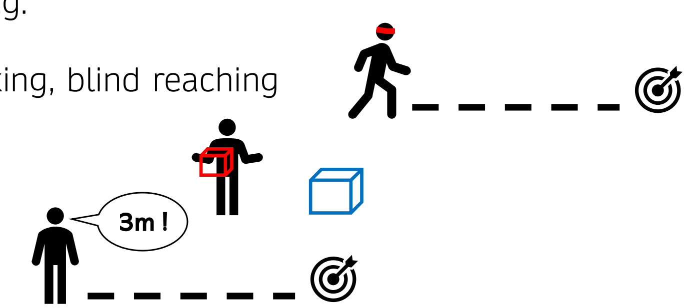
(Renner et al. 2013)

- Technical factors:
  - Hardware: e.g. HMD weight + restricted FOV
  - Lack or distortion of non-pictorial depth cues (e.g. vergence-accommodation conflict, binocular disparity)
  - Graphics' quality
  - Geometric distortions
- Compositional factors:
  - Nature of the virtual environment => pictorial depth cues
  - Presence of self-avatars and objects with familiar size

Human Factors and Measurements

(Renner et al. 2013)

- Human factors:
  - Inter-individual difference between users.
  - Adaptation through feedback interaction.
- Measurements methods:
  - How we measure the distance estimation might also influence the findings.
  - Different tasks have been used, e.g.
    - action-based tasks: blind walking, blind reaching
    - perceptual matching tasks
    - verbal estimates task



Technical Factors: Recent Focus

Comparing different generations of HMDs with different hardware characteristics (FOV, weight, and resolution).
For example, Young et al. (2014), Kelly et al. (2017), and Buck et al. (2018).

- Better estimations when using more recent HMDs:
  - **Oculus Rift DK1** compared to NVIS nVisor SX60 (Young et al. 2014).
  - **HTC Vive** compared to existing data from previous experiments using nVisors SX111 and ST50 (Kelly et al. 2017)
  - **Oculus Rift DK1** and 2 modified versions (heavier and with restricted FOV), nVisors SX60 and SX111 (Exp. 1 of Buck et al. 2018).
- Exp. 2 of Buck et al. 2018: Better performance of **Oculus Rift CV1** compared to HTC Vive, Oculus Rift DK2.

Technical Factors: Recent Focus

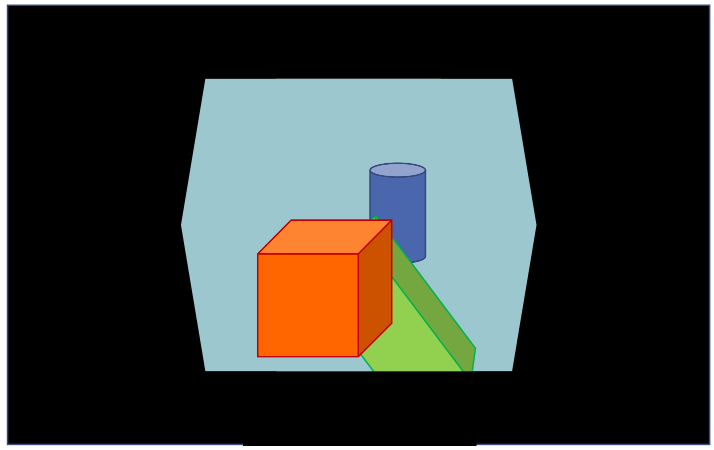
Comparing different generations of HMDs with different hardware characteristics (FOV, weight, and resolution).
For example, Young et al. (2014), Kelly et al. (2017), and Buck et al. (2018).

- Inertia and mass factors showed significant impact on distance perception.
- Limited FOV might impact as well.
  In contrast with previous works. Different experimental designs can be the reason of the different results.

Technical Factors: Recent Focus

Impact of **visual stimulation in the FOV far periphery** (Jones et al. 2016) (Li et al. 2016, 2018)

The following factors resulted to impact positively the distance estimation:

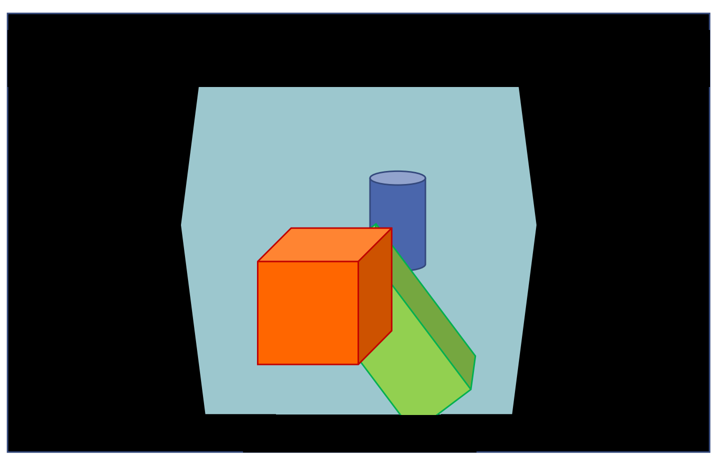


Technical Factors: Recent Focus

Impact of **visual stimulation in the FOV far periphery** (Jones et al. 2016) (Li et al. 2016, 2018)

The following factors resulted to impact positively the distance estimation:

- Extending vertically the FOV (Jones et al. 2016)

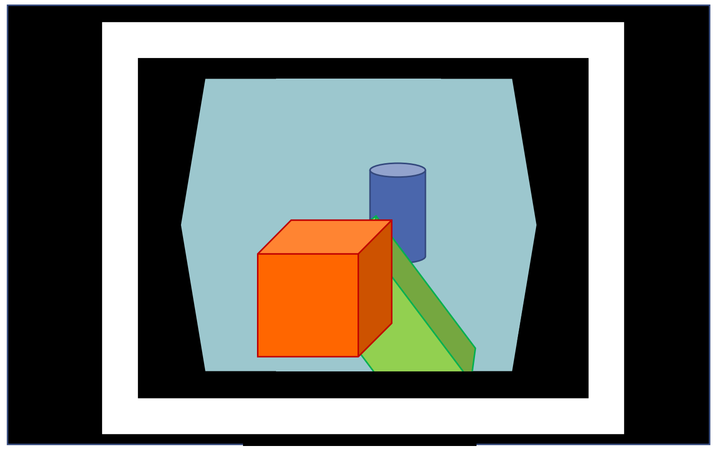


Technical Factors: Recent Focus

Impact of **visual stimulation in the FOV far periphery** (Jones et al. 2016) (Li et al. 2016, 2018)

The following factors resulted to impact positively the distance estimation:

- Extending vertically the FOV (Jones et al. 2016)
- Adding a white frame in the far periphery (Jones et al. 2016)



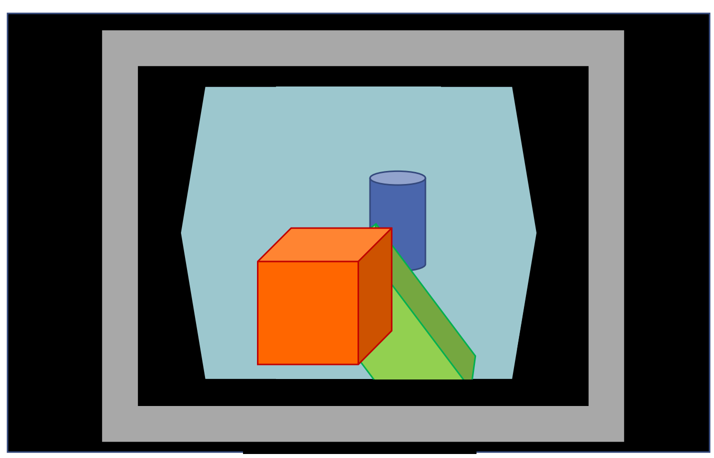
Technical Factors: Recent Focus

Impact of **visual stimulation in the FOV far periphery** (Jones et al. 2016) (Li et al. 2016, 2018)

The following factors resulted to impact positively the distance estimation:

- Extending vertically the FOV (Jones et al. 2016)
- Adding a white frame in the far periphery (Jones et al. 2016)

- Different brightness level of the frame (Li et al. 2018)
  Significant improvement of distance perception adding 15% luminance value relative to the maximum brightness of the frames displayed.



Technical Factors: Recent Focus

Other technical factors recently investigated:

- Eye height manipulation (Leyrer et al. 2015)
  - Proved to affect distance perception, both in VEs with sparse and rich visual cues.
  - Adapting eye height individually, i.e. lowering the eye height, can be used to reduce underestimation.

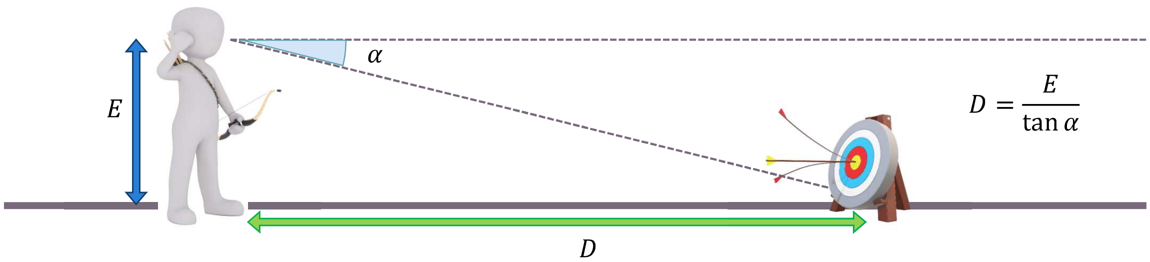
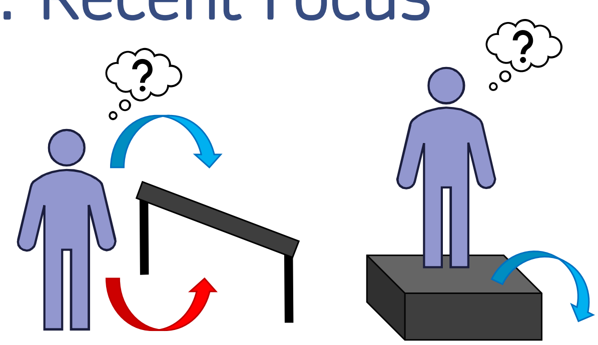


Fig. 2-P3 Adapted from image by Peggy und Marco Lachmann-Anke from Pixabay. Pixabay License.
https://pixabay.com/illustrations/archer-target-archery-bogensport-5443951/

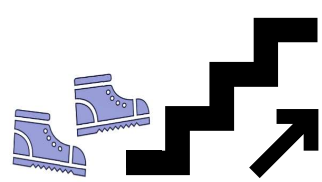
Compositional Factors: Recent Focus

Presence of the self-avatar



(Lin et al. 2015)
Positive impact of a matched-size full self-avatar on affordance tasks.

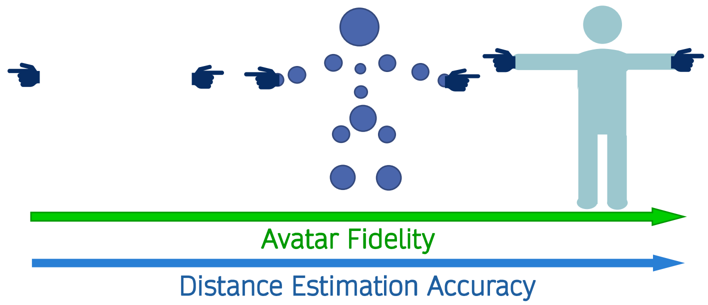
(Asjad et al. 2018)
Investigated the presence of partial avatar (virtual feet) and open or closed VE on distance estimation when climbing stairs. Positive impact of partial avatar and open VE.



Compositional Factors: Recent Focus

Level of visibility of the avatar
(Ebrahimi et al. 2018)
3 conditions:
- end-effectors
- body joint positions
- high-fidelity avatar

High-fidelity avatar induced the best results of near-field distance estimation but still not comparable to the results obtained in real-world condition.



Personalisation of the avatar (Jung et al. 2018)
With a personalised hand model the participants achieved a better accuracy on the size estimation task compared to a generic 3D model of a hand in VR

Compositional Factors: Recent Focus

Different types of self-avatar (Banakou et al. 2013)
Participants were embodied into an avatar of a child, and an avatar as tall as the child but with the body proportion of an adult.
Overestimation of size with both avatars, significantly higher with the child avatar. Results linked to body ownership.

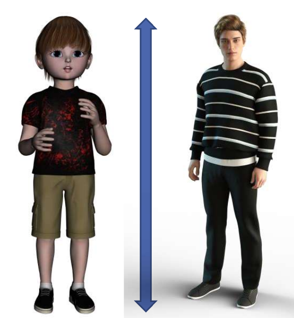


Fig. 3-P3 Fig. 4-P3

Size of a partial self-avatar (Jun et al. 2015)
Tested different sizes of virtual feet.
Changing the size of the virtual feet influence size estimation during affordance judgements of gap crossing and gap-width estimates.
Participants exploited their self-avatar, even if partial, to scale the VE.

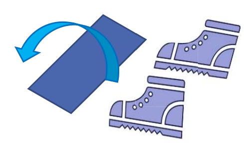


Fig. 3-P3. Adapted from image by Barroa_Artworks from Pixabay. Pixabay License. https://pixabay.com/illustrations/chibi-doll-anime-child-manga-3230107/
Fig. 4-P3. Image by CharacterDesign3D from Pixabay. Pixabay License. https://pixabay.com/illustrations/boy-man-people-guy-person-male-4731631/

Compositional Factors: Recent Focus

Self-avatar with visuomotor conflicts (Kokkinara et al. 2015)
Spatiotemporal distortions (increased velocity) and spatial distortions (angular offset) of self-avatar arm movements affect size estimation.

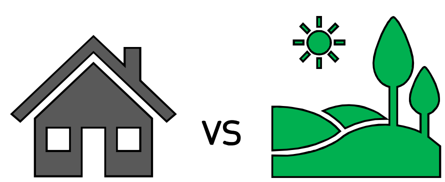
- Targeting task with visible avatar.
- Size estimation task without avatar.

Increased overestimation of size with more amplified distortions (both spatial and spatiotemporal).

Compositional Factors: Recent Focus

Nature of VEs (indoor vs outdoor) **(Kelly et al. 2017)**

- No significant difference for the blind walking task.
- Better performance in the indoor VE for the size judgement task, similar trends but not significant for the verbal judgement task.



Availability of visual cues (Loyola 2018)

- Verbal judgement task while sitting in 3 virtual rooms (low, medium, and high visual cues).
- Accuracy influenced by the level of availability of the visual cues, high availability showed better performance.

Human Factors: Recent Focus

Visual-motor feedback interaction:
Can interaction in the VE (e.g. walking through VE) improve distance perception?

Yes, but there is still open debate about how.
Two main theories:

- Interaction causes only **visual-motor recalibration** (Kunz et al. 2015)
- Interaction causes also **rescaling of the perceived space** (Kelly et al. 2013)

- Results by Siegel and Kelly (2017) support the rescaling theory and that distance estimation improves also in space extended beyond the one used for the interaction.

Human Factors: Recent Focus

Visual-motor feedback interaction:
Can interaction in the VE (e.g. walking through VE) improve distance perception?

(Kelly et al. 2014)

- Interaction to near objects (1 m and 2 m) caused a recalibration of perceived scale only in the same range of distances.
- Interaction to far objects (4 m and 5 m) induced a recalibration over both near and far range of distances.

(Kelly et al. 2017) HTC Vive

- Blind-walking and size judgments were affected by walking interaction.
- Verbal judgments were not affected by walking interaction.

Human Factors: Recent Focus

Visual-motor feedback interaction:
Can interaction in the VE (e.g. walking through VE) improve distance perception?

(Kelly et al. 2018)

- Compared the influence of walking interaction to the influence of having a visual preview of the VE.
- The effect of walking interaction is broader than visual preview, walking interaction might be a more valid method for improving distance perception in VR.

Distance Perception in AR

Depth distortion is also common in AR applications with HMDs. (Kruijff et al. 2010)

Different perceptual issues are related to distance distortion, e.g.

- Color's monotony of the VE.
- Exposure problems, noise, and low contrast when capturing the environment.
- Depth cues: occlusion problems, limited number of depth cues.
- Vergence-accommodation conflict.

Distance Perception in AR: Recent Focus

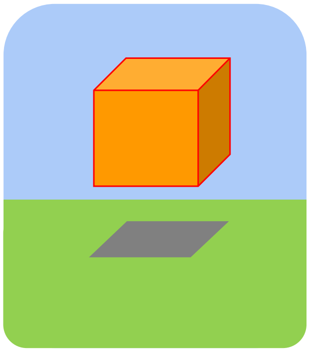
Positive effect of auxiliary augmentations in "X-ray vision" (Kytö et al. 2013)
- In addition to the main virtual object, they displayed auxiliary objects.
- Occlusion and similarity cues exploited.

Study of depth perception at reaching distance (Swan et al. 2015)
- Perceptual matching and blind reaching tasks.
- Overestimation up to 4 cm, possibly due to the collimating optics of the AR see-through display.

Distance Perception in AR: Recent Focus

Impact of different visual effects applied to augmented objects (Diaz et al. 2017)

- Perceptual matching task
- Distance range tested: 2.5 and 6 meters
- Visual effects tested:
  - Aerial perspective
  - **Drop shadows** and **cast shadows**
  - Lambertian, Blinn and Phong shading models
  - Billboarding effect
  - Object dimensionality (2D vs 3D)
  - Textures
- Results:
  - Systematic underestimation of distances.
  - Presence of shadows improved distance judgements.

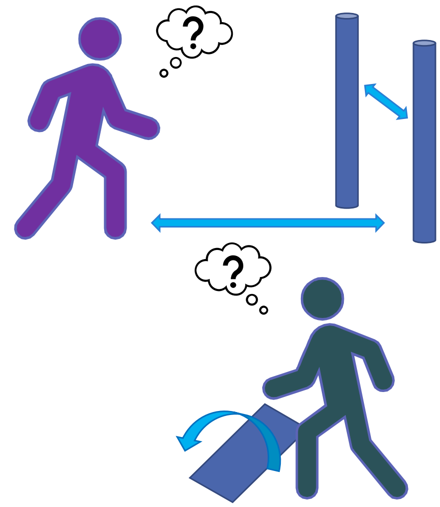


Distance Perception in AR

Distance judgment evaluated with locomotion-based affordance tasks
(Pointon et al. 2018)

- Comparisons between real world and AR
- Passing through 2 poles
- Egocentric distance of the poles
- Gap-crossing

- Results:
  - Similar judgments for passing through and perceived distance to the aperture.
  - Underestimated distance for gap-crossing in AR.



SUMMING UP...

- Hot topic in the research community, more studies in VR than AR, still many open questions and further investigation required.

- Modern HMDs provide better distance estimation accuracy.

- How might we actively improve the user spatial perception?

  - Visual stimulation in the FOV far periphery
  - Eye height manipulation
  - Presence of avatars, high-quality, personalised
  - Interaction, but how?
  - Using specific visual cues

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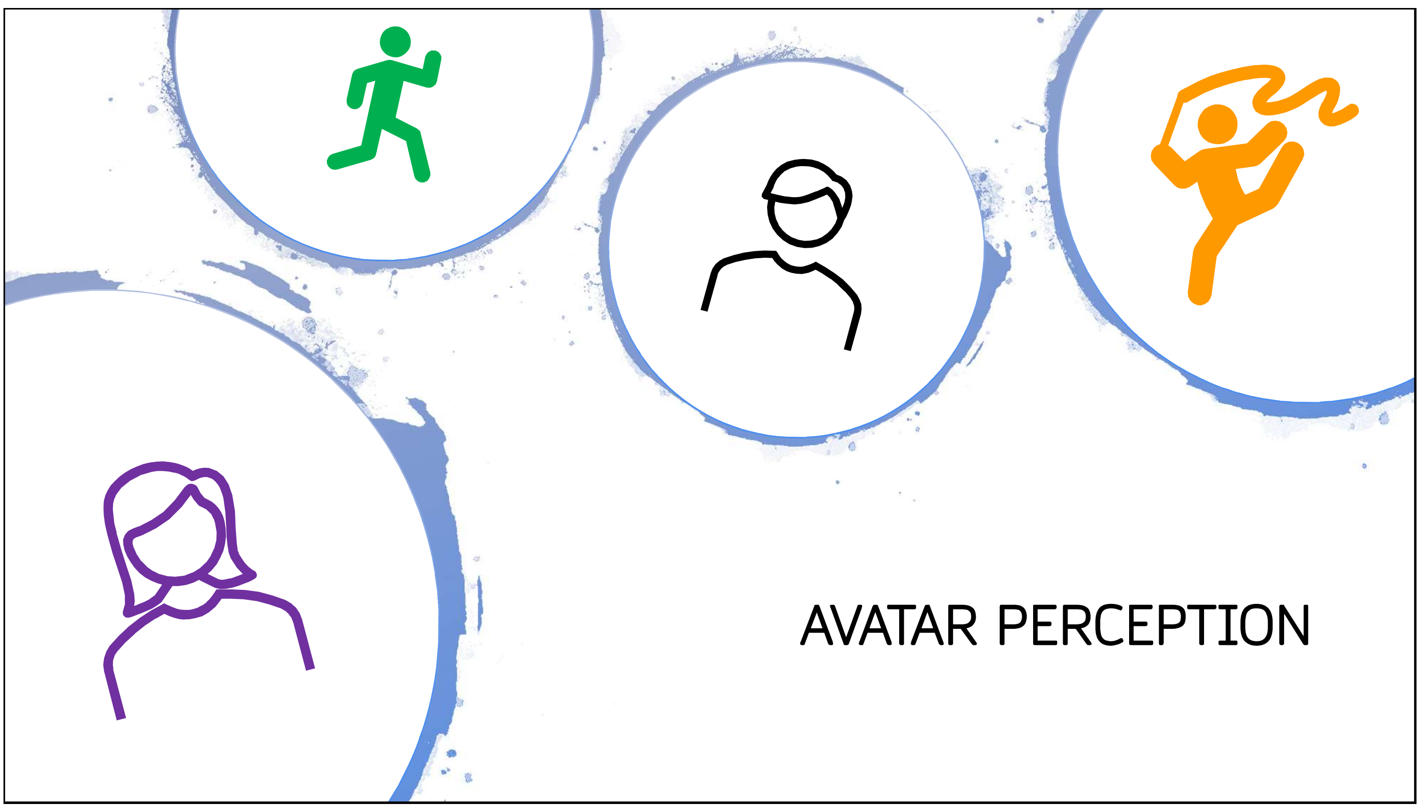


Avatar Influence

How can self-avatar or virtual characters influence the experience in immersive VR?

Fig. 5-P3 Image by Wolfgang Eckert from Pixabay. Pixabay License
https://pixabay.com/illustrations/man-jump-sport-run-fashion-casual-3107153/

AVATAR's VISUAL CHARACTERISTICS:

- Presence or absence of avatar
- Level of visibility of avatar
- Personalisation of avatar
- Level of realism
- Visuomotor conflicts
- ...

ASPECTS of the EXPERIENCE:

- Spatial perception
- Body ownership
- Sense of agency
- Presence
- ...

Aspects Recently Studied

Spatial Perception:

- Compositional factor. (Renner et al. 2013)

Body Ownership:

- Self-attribution of a body, *"I am the one undergoing the experience".* (Kilteni et al. 2012, Gallagher 2000)

Sense of Agency:

- Present in active movements, sense of controlling the action, *"I am the one who is generating an action"*. (Kilteni et al. 2012, Gallagher 2000)

Sense of Presence:

- The sense of "being there".

Levels of body ownership, sense of agency and presence are measured via subjective measurements based on questionnaires.

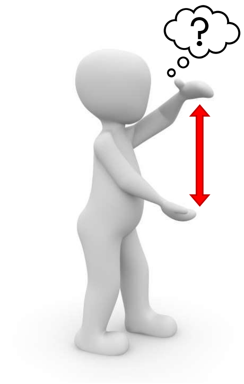
Aspects Recently Studied

	Avatar's Characteristics	Spatial Perception	Body Ownership	Sense of Agency	Presence
Banakou et al. 2013	"type" of avatar visuomotor conflicts	X	X		
Asjad et al. 2018	Presence of partial avatar	X			X
Kokkinara et al. 2015	Presence of avatar with visuomotor conflicts	X	X	X	
Jun et al. 2015	Size of partial avatar	X	X	X	X
Lin et al. 2019	Size of partial avatar		X	X	
Argelaguet et al. 2016	Level of realism of avatar		X	X	
Latoschik et al. 2017	Level of realism of avatar		X		
Lougiakis et al. 2020	Level of realism of avatar		X	X	
Tran et al. 2017	Level of visibility of avatar		X	X	
Lugrin et al. 2018	Level of visibility of avatar		X		
Waltemate et al. 2018	Personalisation of avatar		X		X
Jung et al. 2018	Personalisation of partial avatar	X	X		X

Aspects Recently Studied

	Avatar's Characteristics	Spatial Perception	Body Ownership	Sense of Agency	Presence
Banakou et al. 2013	"type" of avatar visuomotor conflicts	X	X		
Asjad et al. 2018	Presence of partial avatar	X			X
Kokkinara et al. 2015	Presence of avatar with visuomotor conflicts	X	X	X	
Jun et al. 2015	Size of partial avatar	X	X	X	X
Lin et al. 2019	Size of partial avatar		X	X	
Argelaguet et al. 2016	Level of realism of avatar		X	X	
Latoschik et al. 2017	Level of realism of avatar		X		
Lougiakis et al. 2020	Level of realism of avatar		X	X	
Tran et al. 2017	Level of visibility of avatar		X	X	
Lugrin et al. 2018	Level of visibility of avatar		X		
Waltemate et al. 2018	Personalisation of avatar		X		X
Jung et al. 2018	Personalisation of partial avatar	X	X		X

Size and Spatial Perception



We have already discussed avatar as compositional factor influencing distance estimation.
Some works focused specifically on distance perception estimation:

- Presence **(Lin et al. 2015)** and fidelity of avatar **(Ebrahimi et al. 2018)**

Other works investigated the influence of avatars on spatial perception and other factors, i.e. **body ownership, sense of agency, and sense of presence** (Banakou et al. 2013) (Jun et al. 2015) (Asjad et al. 2018) (Jung et al. 2018) (Kokkinara et al. 2015)

Fig. 6-P3 Adapted from image by Peggy und Marco Lachmann-Anke from Pixabay. https://pixabay.com/illustrations/males-3d-model-isolated-3d-model-2506815/

Size and Spatial Perception

Different types of avatar and correlation with body ownership
(Banakou et al. 2013)

Participants were embodied into an avatar of a child, and an avatar as tall as the child but with the body proportion of an adult.

Overestimation of size with both avatars, significantly higher with the child avatar.

They applied visuomotor conflicts (different movements) to lower the body ownership illusion.
Overestimation differences between avatars disappeared.

Influence of the body type on spatial perception is correlated to the body ownership illusion


Fig. 7-P3


Fig. 8-P3

Fig. 7-P3. Adapted from image by Barroa_Artworks from Pixabay. Pixabay License. https://pixabay.com/illustrations/chibi-doll-anime-child-manga-3230107/
Fig. 8-P3. Image by CharacterDesign3D from Pixabay. Pixabay License. https://pixabay.com/illustrations/boy-man-people-guy-person-male-4731631/

Aspects Recently Studied

	Avatar's Characteristics	Spatial Perception	Body Ownership	Sense of Agency	Presence
Banakou et al. 2013	"type" of avatar visuomotor conflicts	X	X		
Asjad et al. 2018	Presence of partial avatar	X			X
Kokkinara et al. 2015	Presence of avatar with visuomotor conflicts	X	X	X	
Jun et al. 2015	Size of partial avatar	X	X	X	X
Lin et al. 2019	Size of partial avatar		X	X	
Argelaguet et al. 2016	Level of realism of avatar		X	X	
Latoschik et al. 2017	Level of realism of avatar		X		
Lougiakis et al. 2020	Level of realism of avatar		X	X	
Tran et al. 2017	Level of visibility of avatar		X	X	
Lugrin et al. 2018	Level of visibility of avatar		X		
Waltemate et al. 2018	Personalisation of avatar		X		X
Jung et al. 2018	Personalisation of partial avatar	X	X		X

Body Ownership

Avatar's characteristics analysed to study their impact on the perception of body ownership:

	Avatar's Characteristics	Impact	
Banakou et al. 2013	visuomotor conflicts	✓	Visuomotor conflicts: avatar making different movements.
Kokkinara et al. 2015	Presence of avatar with visuomotor conflicts	✗	Both spatial and spatiotemporal manipulations did not affect body ownership perception.
Jun et al. 2015	Size of partial avatar	✗	Small and large foot size conditions.
Lin et al. 2019	Size of partial avatar	✗	Small, fit, and large hand size conditions.
Argelaguet et al. 2016	Level of realism of partial avatar	✓	3 conditions: sphere, robotic hand (limited animation), realistic human hand (fully animated). The realistic hand condition achieved higher sense of body ownership.
Latoschik et al. 2017	Level of realism of avatar	✓	2 conditions: wooden mannequin and high-fidelity avatar. Higher level of body ownership with increasing level of fidelity of self-avatar.
Lougiakis et al. 2020	Level of realism of partial avatar	✓	3 conditions: sphere, controller, realistic human hand. No finger tracking (participants used a controller in all condition).
Tran et al. 2017	Level of visibility of avatar	✗	3 conditions: hand only, hand + forearm, and whole arm.
Lugrin et al. 2018	Level of visibility of avatar	✗	3 conditions: controller, hand + forearm, upper body (limited tracking).
Waltemate et al. 2018	Personalisation of avatar	✓	3 conditions: personalised avatar with 3D scan system, generic avatar 3D scan system and a modelled generic avatar.
Jung et al. 2018	Personalisation of partial avatar	✓	Personalised hand vs generic hand model conditions

Aspects Recently Studied

	Avatar's Characteristics	Spatial Perception	Body Ownership	Sense of Agency	Presence
Banakou et al. 2013	"type" of avatar visuomotor conflicts	X	X		
Asjad et al. 2018	Presence of partial avatar	X			X
Kokkinara et al. 2015	Presence of avatar with visuomotor conflicts	X	X	X	
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Lin et al. 2019	Size of partial avatar		X	X	
Argelaguet et al. 2016	Level of realism of avatar		X	X	
Latoschik et al. 2017	Level of realism of avatar		X		
Lougiakis et al. 2020	Level of realism of avatar		X	X	
Tran et al. 2017	Level of visibility of avatar		X	X	
Lugrin et al. 2018	Level of visibility of avatar		X		
Waltemate et al. 2018	Personalisation of avatar		X		X
Jung et al. 2018	Personalisation of partial avatar	X	X		X

Sense of Agency

Avatar's characteristics analysed to study their impact on the perception of sense of agency:

	Avatar's Characteristics	Impact	
Kokkinara et al. 2015	Presence of avatar with visuomotor conflicts	✓	Only spatiotemporal (velocity) manipulations affected the sense of agency.
Jun et al. 2015	Size of partial avatar	✗	Small and large foot size conditions.
Lin et al. 2019	Size of partial avatar	✗	Small, fit, and large hand size conditions.
Argelaguet et al. 2016	Level of realism of avatar	✓	3 conditions: sphere, robotic hand (limited animation), realistic human hand (fully animated). The realistic hand condition achieved low sense of agency, potentially due to limitations in finger tracking.
Lougiakis et al. 2020	Level of realism of avatar	✗	3 conditions: sphere, controller, and realistic human hand. No finger tracking (participants used a controller in all condition).
Tran et al. 2017	Level of visibility of avatar	✗	3 conditions: hand only, hand + forearm, and whole arm.

Aspects Recently Studied

	Avatar's Characteristics	Spatial Perception	Body Ownership	Sense of Agency	Presence
Banakou et al. 2013	"type" of avatar visuomotor conflicts	X	X		
Asjad et al. 2018	Presence of partial avatar	X			X
Kokkinara et al. 2015	Presence of avatar with visuomotor conflicts	X	X	X	
Jun et al. 2015	Size of partial avatar	X	X	X	X
Lin et al. 2019	Size of partial avatar		X	X	
Argelaguet et al. 2016	Level of realism of avatar		X	X	
Latoschik et al. 2017	Level of realism of avatar		X		
Lougiakis et al. 2020	Level of realism of avatar		X	X	
Tran et al. 2017	Level of visibility of avatar		X	X	
Lugrin et al. 2018	Level of visibility of avatar		X		
Waltemate et al. 2018	Personalisation of avatar		X		X
Jung et al. 2018	Personalisation of partial avatar	X	X		X

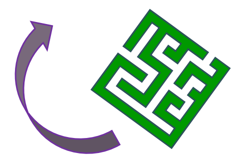
Sense of Presence

Avatar's characteristics analysed to study their impact on the perception of sense of presence:

	Avatar's Characteristics	Impact	
Asjad et al. 2018	Presence of partial avatar	✓	Presence of avatar, even if partial, showed significantly higher level of sense of presence.
Jun et al. 2015	Size of partial avatar	✗	Small and large foot size conditions.
Waltemate et al. 2018	Personalisation of avatar	✓	3 conditions: personalised avatar with 3D scan system, generic avatar 3D scan system and a modelled generic avatar. Personalised avatar achieved higher sense of presence.
Jung et al. 2018	Personalisation of partial avatar	✓	2 conditions: personalised hand and generic hand model. Personalised hand achieved higher sense of presence.

Cognitive Processes

(Steed et al. 2016)
Positive influence of the presence of an active avatar when performing cognitive tasks.
Set of cognitive tasks:
- memorization of sequences of letters
- mental rotation of figures
- recollection of sequences of letters

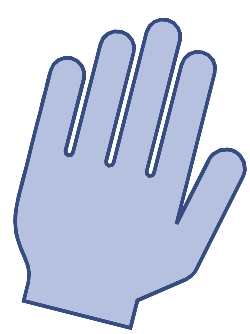


Significant effect on cognitive performance when participants viewed their avatar and were allowed to make gestures.

Avatar in AR

We found also a limited number of studies about avatar in AR.

(Skola and Liarokapis 2016)
Compared the effects on body ownership rubber hand illusion performed in VR, AR, and in the real world.
Still stronger sense of ownership for the real world condition but VR and AR are comparable.
Electroencephalography (EEG) measures correlated with subjective measures (questionnaire) for body ownership.



Avatar in AR

(Kim et al. 2017)
Influence on social presence and co-presence of spatial conflicts between AR virtual characters and the real world environment.

Results showed a lower sense of co-presence for the conflict condition.

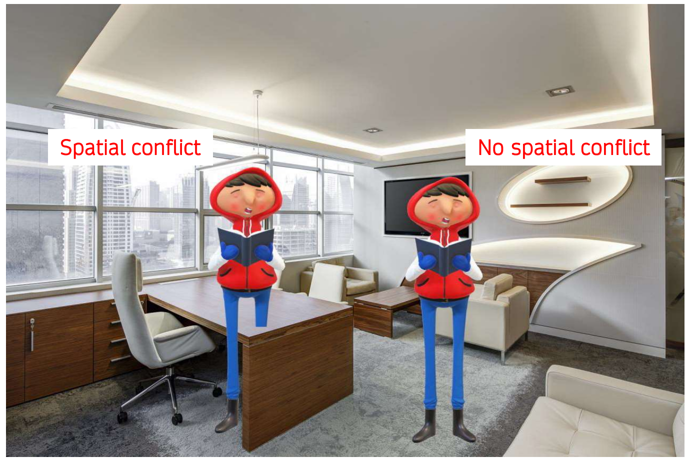


Fig. 9-P3 Adapted from image by MagicDesk from Pixabay. Pixabay License
https://pixabay.com/photos/office-sitting-room-executive-730681/

SUMMING UP…

- The presence of an avatar and its visual characteristics (realism, fidelity …) impact many different aspects of the immersive experience.
- These aspects are not independent, e.g. (Banakou et al. 2013).
- Body ownership and sense of presence are connected to presence of the avatar but also the level of realism and personalisation of the avatar.
- Sense of agency is more connected to the interaction than the visual characteristics of the avatar.
- Majority of the analysed works are in VR.
- In AR, spatial conflicts between virtual character and real object can affect the sense of co-presence.

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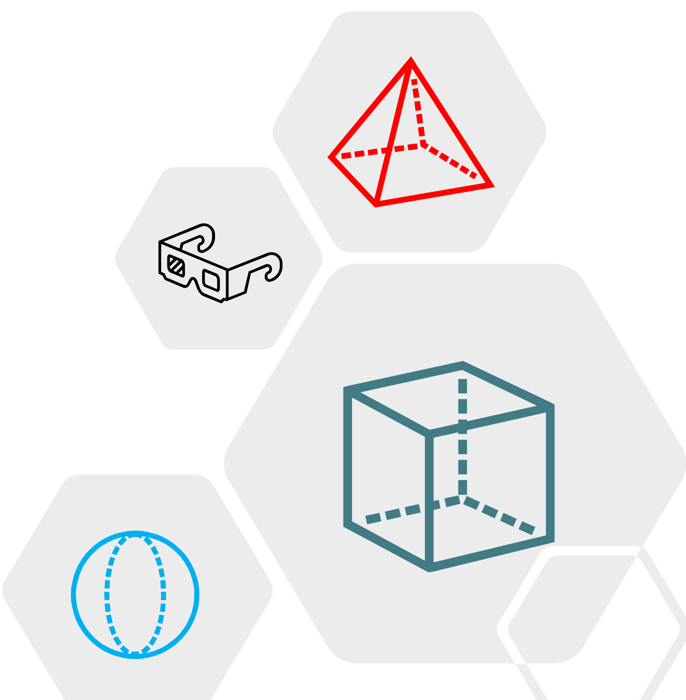
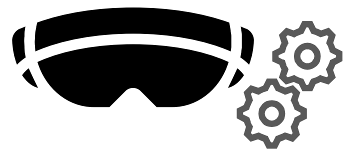


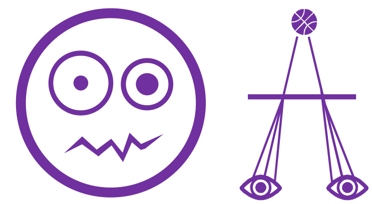
IMAGE QUALITY

Some HMD Hardware Limitations

- Limited computational power.



- Vergence-accommodation conflicts.



- Wearing glasses for optical correction is not always possible.

HMD Application Requirements

Higher resolutions and bigger FOVs demand:

- Low latency rendering
- High quality rendering

Subjective Quality and Performance

How can we exploit the characteristics of the human visual system (HVS) for improving quality perceived by the user and performance?

Visual acuity and visual attention to reduce shading cost!

- Perceptual foveated rendering
- Perceptual rendering
- Visual saliency prediction
- …

Foveated Rendering

Non-uniform quality of the rendered image. Highest level of detail in the area around the eye fixation. Progressively lower quality distancing from the eye fixation area.

Exploiting visual acuity degradation, we can obtain rendering speedups while maintaining a perceptually high-quality result for the human observer.

Not new idea! e.g. Gaze-directed Volume Rendering by **Levoy and Whitaker (1990)**

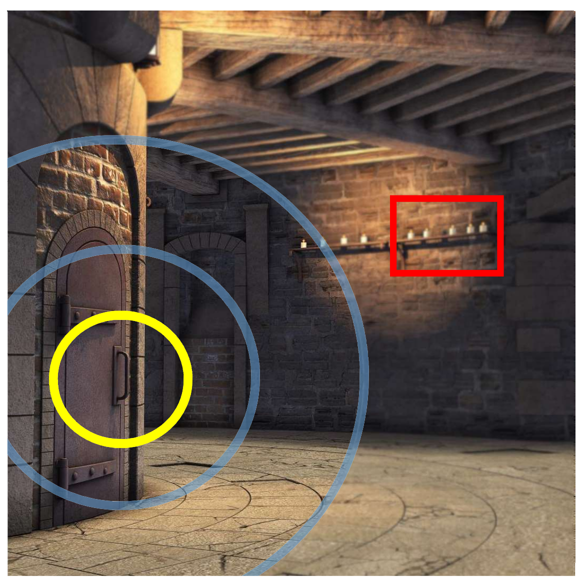


Fig. 10-P3 Adapted from image by Wolfgang Eckert from Pixabay. Pixabay License. https://pixabay.com/photos/tower-rotunda-candlelight-candles-3362555/

Foveated Rendering

(Patney et al. 2016) Oculus Rift DK2 + SMI eye tracker

1) User study to investigate the perceived quality on peripheral vision, defining a perceptual target image.
2) Design a real-time foveated renderer to match the target image (contrast enhancement and temporal antialiasing).
3) User study to verify the quality of the foveated renderer.

(Weier et al. 2016) Oculus Rift DK2 + SMI eye tracker

- Foveated rendering + reprojection rendering using previous frames.
- Resampling of perceptually critical areas and reprojection errors.

Foveated Rendering

(Stengel et al. 2016)

- Deferred rendering: simulation of acuity falloff + sampling scheme considering:
  - Acuity
  - Eye motion
  - Contrast (geometry, material, and lighting properties)
  - Brightness adaptation

(Swafford et al. 2016)

- Design of a perceptual foveated rendering quality metric based on HDR-VDP2 (Mantiuk et al. 2011)

Foveated Rendering

(Arabadzhiyska et al. 2017) Oculus Rift DK2 + Pupil Labs eye tracker

- System latency causes a mismatch between the actual fixation point and the rendered foveated region.
- They propose a technique which predicts where the saccadic eye movement is likely to end up.

(Weier et al. 2018) Fove 0

- Exploiting visual acuity degradation and Depth-of-Field (DoF) effect.
- Foveated renderer with gaze-contingent DoF filtering as post-processing step to hide visual artifacts and remove high-frequency signals on the periphery.
- DoF effect is scene dependent!

Contrast Enhancement

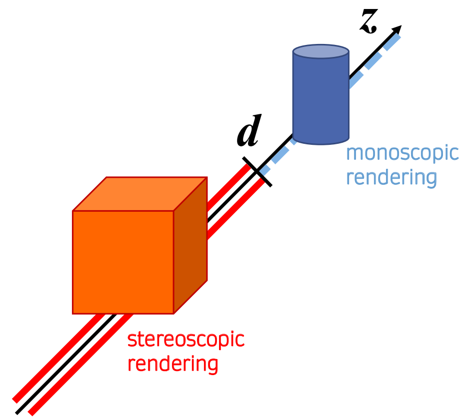
(Zhong et al. 2019) HTC Vive

- Image contrast is linked to perceived quality: contrast-based depth induction and higher realism.
- How can we enhance contrast in VR/AR displays?
  - High Dynamic Range HDR: flickering and higher power consumption.
  - Local tone-mapping: artifacts, computational expensive.
- Proposed technique: exploit binocular fusion mechanisms of HVS to enhance perceived contrast using different tone curve for each eye.
- Trade-off between contrast enhancement and binocular rivalry.
- User study showed better perception of contrast and depth.

Binocular Disparity

(Fink et al. 2019) HTC Vive

- How to improve rendering computational efficiency?
- Proposed technique exploits binocular disparities and the fact that they are more significant in the near field (Cutting and Vishton 1995)
- Stereoscopic rendering of objects only up to a fixed distance and monoscopic rendering for objects placed at higher distances.



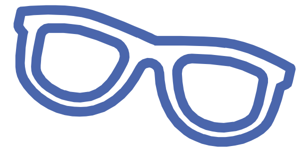
Saliency Prediction

(Celikcan et al. 2020) HTC Vive

Exploring visual saliency cues and saliency prediction methods applied on immersive dynamic VR content.

- Methods using 2D image features
- Methods using 2D image features + depth cue: RGB-D input
- With lower navigation speed the depth cue has lower impact on visual saliency.
- Better performance of saliency prediction methods based on boundary connectivity and surroundedness.
- Center bias (Sitzmann et al. 2018) confirmed also in this work, more significant in the VR view compared to the 2D monitor.

Handling Refractive Errors



(Padmanaban et al. 2017) Samsung Gear VR + SMI eye tracker

- Near-eye displays limitations, limited reproduction of focus changes.
- Adaptive focus display:
  - Adapting to different user groups (younger vs older users).
  - Handling user refractive errors.

(Xu and Li 2018) Oculus Rift DK2

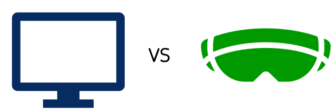
- Rendering pre-corrected images to handle user refractive errors.

Quality Assessment in VR

(Pardo et al. 2018) Oculus Rift DK2

- Subjective assessment of level of realism of scanned 3D replicas of real objects, rendered with deferred or forward rendering in real-time.
- Better realism achieved by the deferred rendering.
- Color fidelity and material texture, and definition of the 3D replicas are the main factors correlated to realism perception.

(Yu et al. 2018) HTC Vive



- Comparing subjective quality assessment on 2D monitor and HMD of 3D polygon meshes impaired with smooth and noise-like distortions.
- No significant differences between the two types of display.

Quality Assessment in AR

(Alexiou et al. 2017) Occipital Bridge AR

- Subjective quality assessment of 3D points clouds with noise and octree-pruning (compression) distortions.
- Results showed high level of correlation between subjective assessments and objective metrics, e.g. point2point, point2plane, Peak-to-Signal Noise Ratio (PSRN) for noise distortions, not for compression-like distortion.

(Alexiou and Ebrahimi 2018) Occipital Bridge AR

- Investigated the correlation between subjective quality assessments of distorted AR points clouds conducted using a 2D screen and an HMD.
- Noise degradation: high correlation between the monitor and HMD.
- For compression-like distortion: different results based on the display techniques.

SUMMING UP…

- Foveated rendering is promising technique to improve the rendering performance and the perceived quality.
- Visual acuity is not the only visual perception property that can be exploited.
- No unique solution, the combination of different strategy can be explored.
- Perceptual rendering: exploiting the stereo characteristics of the HMD to enhance image appearance or improve the rendering performance.
- Handling refractive errors at software level.
- Quality assessment both in VR and AR of 3D models with distortion, results vary between VR/AR.

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PART IV

RECENT TRENDS AND CHALLENGES IN INTERACTION, MOTION PERCEPTION, AND CYBERSICKNESS

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INTERACTION

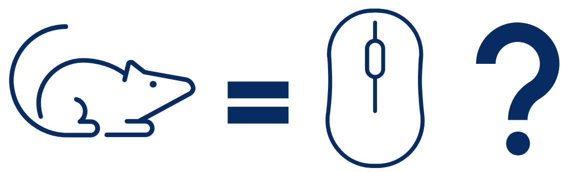
Perception in Interaction Studies

- Human-Computer Interaction (HCI):
  - Design and implementation of novel interaction techniques.
  - Performance evaluation of interaction techniques.

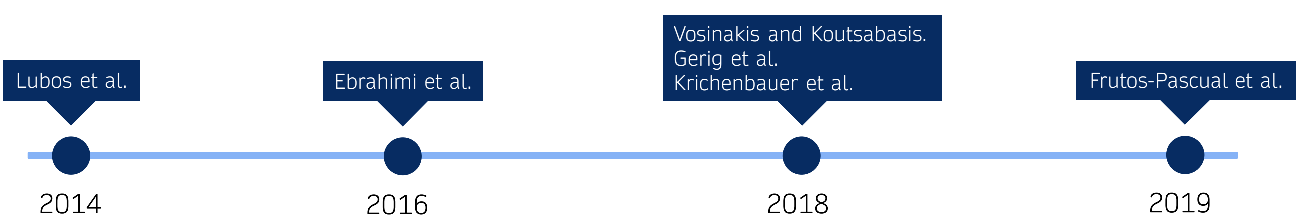
- In Perception studies we have a slightly different focus.

Perception in Interaction Studies

- Perceived quality of experience when using novel interaction techniques.
- Exploit the human visual system to improve interaction perception.
- Evaluation criteria:
  - Efficiency.
  - Consistency.
  - Usability.
  - Psychological affect.



Interaction Studies



Interaction Possibilities with VR

- Majority of reported studies focus on tactile perception with virtual objects:
  - Selecting.
  - Grabbing.
  - Dropping.
  - Pushing, moving.
- Technologies:
  - HMD + Controllers.
  - Joysticks, game pads.
  - Leap Motion.

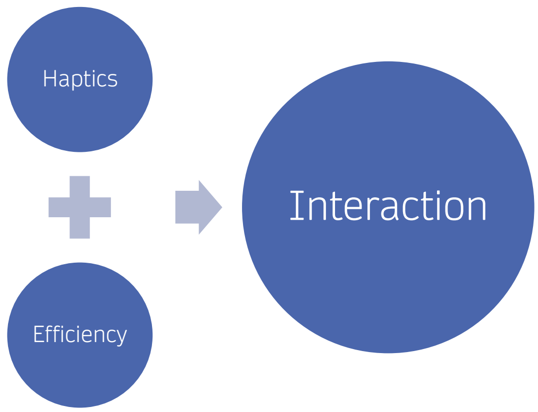
Interaction Possibilities with AR

- Two kinds of interaction (Frutos-Pascual et al., 2019):
  - Metamorphic mapped interaction (emulation of point and click).
  - Isomorphic mapped interaction (direct spatial interaction).
- Technologies:
  - HoloLens.
  - Meta2.

Fig. 1-P4 Image by Azminsultana from Pixabay. Pixabay License.
https://pixabay.com/photos/hololens-holo-lens-virtual-reality-1330225/

Trends in Interaction Perception

- The retrieved material highlighted two major trends in interaction perception studies:



Interaction: Haptics

- *Haptics*: active exploration of the environment through tactile perception (Gibson, 1966).

- The problem: Lack of haptic feedback in VE.
  - Affects immersion, and perceived efficiency and consistency of the interaction.

- Hardware solution: Haptic gloves.
  - Haptx.
  - Manus VR.
  - SenseGlove.

Interaction: Haptics

- *Visual feedback*: dynamic graphical attributes that react to the user proximity or touch.
  - Halos.
  - Color/textures changes.
  - Scaling.
- Improve accuracy as much as visuo-haptic methods. Haptic tradeoff: accuracy is directly proportional to completion time (Ebrahimi et al. 2016).
- Colored halos were reported as more usable among other visual feedback techniques (Vosinakis and Koutsabasis 2018).

Interaction: Efficiency

- The problem: decrement of perceived accuracy and inappropriate functionality of interaction techniques.
- Lack of feedback (visual, haptic) can contribute to this issue.
- When and how do the accuracy errors occur? (Lubos et al. 2014)
  - Viewing direction error > movement direction error.
  - Visual perception has a more predominant influence than movement in ed VE.

Interaction: Efficiency

- Visual and visuo-haptic feedback can help improving the perceived efficiency of interaction techniques.

- HMD vs Flat Screen (Gerig, 2018)
  - Tactile interaction in VE was more consistent and efficient when shown in HMDs.

- AR vs VR (Krichenbauer et al. 2018)
  - In tactile interaction, AR seems superior than VR in terms of efficiency even with no visual feedback techniques.

Challenges with Interaction in Perception Studies

- Interaction is usually evaluated from the HCI perspective.
  - Perception offers a refreshing perspective for analysing interaction.

- Natural lack of haptic feedback in VR/AR.

- Haptic tradeoff.

- Predominant effect of visual perception in low efficiency:
  - Graphical properties and responsiveness of the VE.

- Greater number of studies focusing on VR than AR.

MOTION PERCEPTION

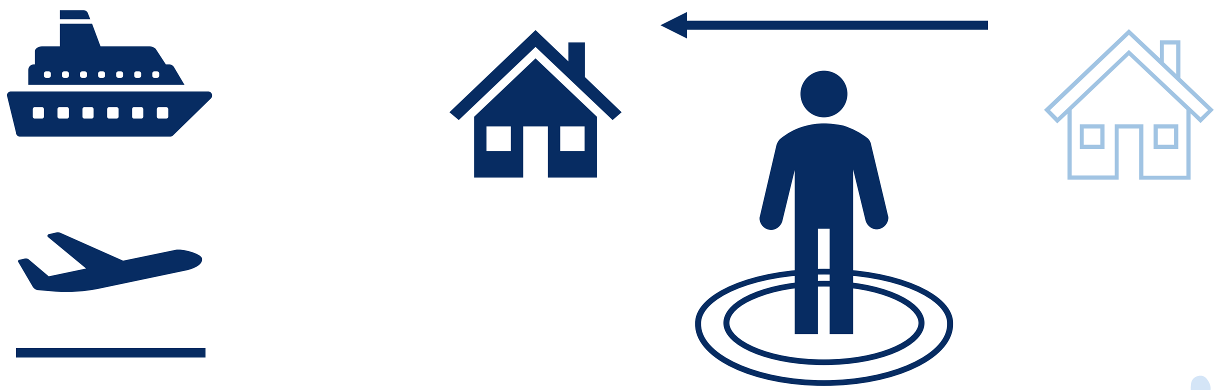
Motion Perception

- Motion: (Borst and Euler 2011) relative inference of **speed**, **position** and **direction** based on:
  - Vestibular state.
  - Proprioceptive inputs.
  - **Visual stimuli.**

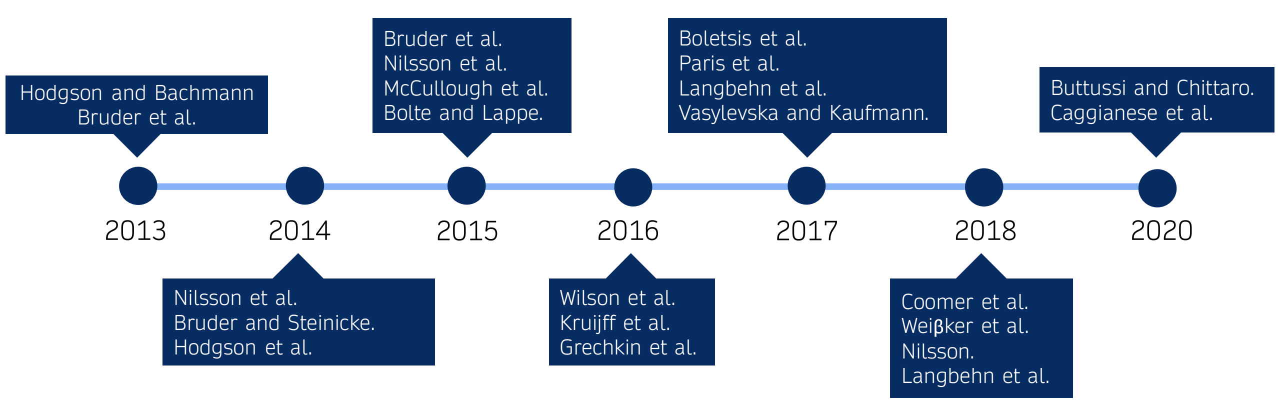
- Take advantage of the human vison system to present techniques that emulate or ease navigation through VE.

Motion Perception

- Vection: Illusion of experiencing self-movement induced by a particular stimuli (Keshavarz et al. 2019)

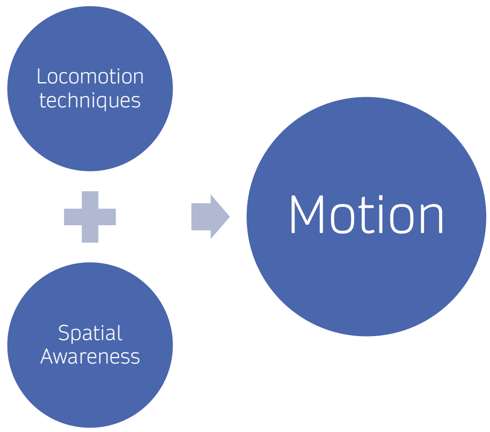


Motion Perception Studies



Trends in Motion Perception

- The retrieved material highlighted two major trends in motion perception studies:



Locomotion Techniques

- Set of methodologies that grant the ability of moving from one place to another within a VE.

- Locomotion techniques (Boletsis 2017):
  - Room scale-based.
  - Motion-based.
  - Controller based.
  - Teleportation based.

Locomotion Techniques

- Room scale-based:
  - Direct mapping of position and orientation between the real world and the VE (e.g. real walking)
  - Good for immersion.
- Motion-based:
  - Physical moments activate locomotion while being stationary (e.g. walking in place).
  - Features many interaction options.

Locomotion Techniques

- Controller-based:
  - Movement is triggered through a controller device.
  - VR controller, joystick, etc.
- Teleportation-based:
  - Instant displacement inside the VE between predefined locations.

Locomotion Techniques

- The problem with locomotion techniques:
  - Performance between different locomotion technique.
  - Limitations space and functionality.

Locomotion Techniques

- Motion-based techniques using alternative technology:
- Myo accelerometer band:
  - *Arm swing*: performs better that some controllers and matches room scale-based performance (McCullough et al. 2015).
  - *Walking in place* was not as effective (Wilson et al. 2016).
  - *Arm cycling*: performs better than controller-based and teleportation-based techniques (Coomer et al. 2018).
- Leap Motion:
  - Hand gesture-based motion (Caggianese et al. 2020).

Locomotion Techniques

- Motion-based techniques using alternative technology:
- Eye tracking:
  - Visual suppression techniques.
  - Gaze pointing motion (Caggianese et al. 2020).

Locomotion Techniques

- *Re-Directed Walking* (RDW) (Nilsson et al. 2018):
  - Reduces the size needed for motion.
  - Users walk on a curved path, thinking they are walking straight.
  - Rotations are imperceptible to viewers.
  - Algorithms used (Hodgson and Bachmann 2013-2014):
    - **Steer-to-center.**
    - **Steer-to-orbit.**
    - Steer-to-multiple targets.
    - Steer-to-multiple+center.
  - RWD results are VE dependent.

Locomotion Techniques

- With larger curves, it was easier for viewers to spot visual anomalies (Bruder et al. 2015).
- Detection of curvatures thresholds in RDW:
  - Green's maximum likelihood procedure (Grechkin et al. 2016).
  - Curvature gains based on conscious eye blinking (Langbehn et al. 2017-2018).
- Saccadic suppression of Image displacement (SSID)
  - Detect threshold based on user fixations and saccadic movements (Bolte and Lappe 2015).

Spatial Awareness

- Refers to the ability to understand, establish, and remember relationships between objects, space and oneself.
- The problem with spatial awareness:
  - How different techniques affect self-motion perception.
  - Inconsistencies between mental models from the real world (location, speed) and the VE.

Spatial Awareness

- A higher level of spatial awareness is achieved with room-based than motion-based techniques, due to the coherence between the real world and the VE (Paris et al. 2017).
- Arm cycling reported better spatial awareness than controller-based and teleportation-based techniques (Commer et al. 2018).
- Controller-based and teleportation-based techniques do not seem to offer different results between one another (Weiβker et al. 2018).

Spatial Awareness

- RDW and VE layout:
  - Curved corridors tend to increase the distance perceived (Vasylevska and Kaufmann 2017a).
  - Participants made larger lateral movements when performing an additional cognitive task (Bruder et al. 2015).
- Scene Manipulation:
  - Self-overlapping virtual environments (Vasylevska and Kaufmman 2017b).

Spatial Awareness

- Perception of motion speed (Nilsson et al. 2014):
  - Do not seem vary significantly between motion-based techniques.
  - FOV and GFOV size in inversely proportional to the degree of underestimation of virtual speed (Nilsson et al. 2015).
- Room scale-based techniques tend to induce an underestimation on distance (large), and speed (small) (Bruder and Steinicke 2014).
- Visuo-haptic cues in VE, together with head bobbing simulation, benefits motion perception without affecting cybersickness (Kruijff et al. 2016).

From Motion Perception Studies

- Walking in place seems to be preferred by users and offer overall good results.
- Visual suppression mechanism are interesting methods to compensate for the drawbacks in room scale-based and motion-based locomotion.
- Combination of different techniques to further improve results (e.g. RDW+SSID).
- Teleportation-based techniques generates less nausea and tend to perform better than controller-based techniques. (Buttussi and Chittaro 2020).

Challenges with Motion in Perception Studies

- Movement within VE is still complex (hardware setup, physical space, spatial awareness).
- For room scale-based: *Tradeoff* between room scale and tracking accuracy, and visuo-vestibular distorting.
- Mixed results between walking in place vs real walking.
- Overcompensation of covered distances when experiencing motion in VE.
- Real walking in VE: Great underestimation of distance and lesser on speed in VR.
- Real walking in AR: minor underestimation of user speed due to the similarity of real-world scenarios (Bruder et al. 2013).

Challenges with Motion in Perception Studies

- They way VE are presented affects the quality of motion (higher motion speeds in AR).
- In RDW, when the rotation is too big, visual anomalies are more noticeable.
- Detection of RDW threshold to improve motion perception.
- RDW seems to have a higher cognitive impact in users*.
- Not many studies focused on AR.
- Linear and angular speeds thresholds for motion techniques.

CYBERSICKNESS

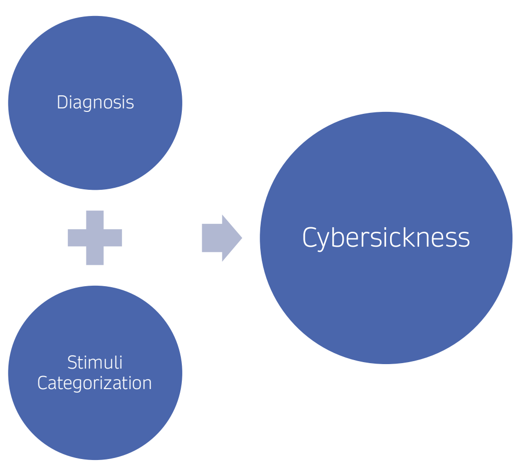
Cybersickness

- Undesired Visually-induced motion sickness experience caused by virtual environment stimuli (Rebenitsch and Owen 2016).
- Manifest as a conflict or disassociation between the **visual** and **vestibular** system (Adhanom et al. 2020).
  - Type of motion sickness specific to the VR/AR domain.
- Many terms to describe same/similar symptoms:
  - Virtual simulation sickness
  - Visual induces motion sickness (VIMS)
  - Simulator sickness.

Cybersickness in VR / AR

Trends in Cybersickness

- The retrieved material highlighted two major trends in studies related to cybersickness:



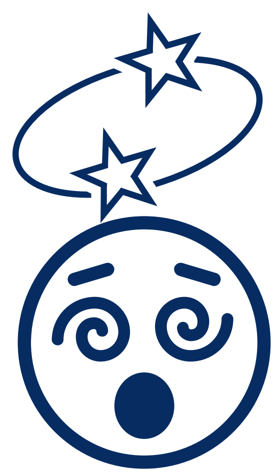
Diagnosis

- Refers to the identification of nature and symptoms of cybersickness.

- The problem with Diagnosis:
  - How to identify, measure, and prevent cybersickness?

Diagnosis

- Symptoms (Rebenitsch and Owen 2016):
  - Nausea
  - Pale skin
  - Cold sweats
  - Vomiting
  - Dizziness
  - Headache
  - Increased salivation
  - Fatigue
  - Eyestrain
  - Difficulty focusing.



Diagnosis

- **Assessing cybersickness:**

- Subjective measures:
  - Simulator sickness questionnaire (SSQ) (Kennedy et al. 1993)

- Objective measures:
  - Postural instability theory (Riccio and Stoffregen 1991).
  - Physiological measurements:
    - Electrodermographic Analysis (EDA).
    - Electrocardiogram (ECG).
    - Blood pressure.
    - Facial temperature.

Diagnosis

- Some of the most common theories explaining the **nature of cybersickness**:
  - *Sensory mismatch*: Visual, vestibular and proprioceptive (Palmisano et al. 2017).
  - *Postural instability*: low sense of balance and righting reflexes (Munafo et al. 2017, Arcioni et al. 2018).
  - *Rapid eye movements*: the vagal nerve can be triggered by rapid involuntary eye movements induced by optical flow or visual patterns (Adhanom et al. 2020).

- In the exploration of cybersickness, there is another issue relevant for a discussion in visual perception: Visual fatigue.

Diagnosis

- *Visual fatigue*:
  - Vergence-Accommodation conflict featured in the eyes, induced by long exposures to screens.
  - (Guo et al. 2020) investigated visual discomfort in long-term VE immersion sessions (8 hours) compare to real physical environment (standard monitor)

- Measuring Visual fatigue:
  - Subjective measures:
    - Visual Fatigue Scale (Kuze and Ukai 2008).
  - Objective measures:
    - Physiological measures:
    - Pupil diameter, accommodation response, and eye blink rate. (Guo et al. 2020).

Diagnosis

- How to **predict** cybersickness?
  - VR sickness predictor: framework for cybersickness metrics (Kim et al. 2018).
  - Camera Trajectories: system evaluates the impact of camera movements based on the path and the speed the camera moves (Hu et al. 2019, Balasubrananian and Soundararajan 2019).

- These approaches are still on an early stage.

Diagnosis

- **Preventing** Cybersickness:
  - Reducing optical flow exposure, e.g. teleportation (CONS: reduced sense of presence and spatial awareness)
  - Reducing the FOV (Adhanom et al. 2020). It can, however, induce more cybersicknes in eccentric gaze behavior.
  - Foveated FOV restrictors: No significantly different results from previous FOV techniques but offered a better gaze dispersion, granting a wider FOV to users (Adhanom et al. 2020).
  - Optimizing camera path-defined movements, based on variations of accelaration, rotation velocity (Hu et al. 2019, Balasubrananian and Soundararajan 2019).
  - Presenting a stationary setup for participants when possible (sitting and still VE).

Stimuli Categorization

- Evaluate the role of different type of applications and visualization techniques in cybersickness.

- The problem with Stimuli:
  - Identify the type of stimuli that can induce cybersickness.

Stimuli Categorization

- It seems there is an inverse relationship between vection and cybersickness, when head movements are analysed (Palmisano et al. 2017):
  - Vection increases when the application compensates head movements.
  - Cybersickness increases in inversely compensated head movements.

- Postural stability test through balancing trials in VR (Munafo et al. 2017):
  - First-person perspective is propense to induce cybersickness.
  - Females report a higher incidence of cybersickness.
  - Correlation between postural sway and cybersickness (Arcioni et al. 2018).

Stimuli Categorization

- AR, using see-through HMDs report (Vovk et al. 2018):
  - Low rates of cybersickness.
  - Oculomotor distress as the most common symptom.

From Cybersickness Studies

- Heavily focused in the area of VR.

- Effects of that may induce cybersickness:
  - Rendering options (monoscopic, stereoscopic).
  - FOV.
  - Body sway and postural instability.
  - Camera trajectories.
  - The graphical properties of the application itself.

From Cybersickness Studies

- Postural instability theory: general postural control correlates with tendency of perceiving cybersickness in games (Munafo et al. 2017) and controlled environments (Arcioni et al. 2018).

- Biological sex may also be a factor for cybersickness (Munafo et al. 2017).

- The development of frameworks to estimate cybersickness may aid in the scalability of the research done in the area (Kim et al. 2018).

- See-through HMDs seem to reduce the perception of cybersickness (Vovk et al. 2018).

Challenges in Cybersickness Studies

- Many factors may affect the perception of Cybersickness:
  - Body sway, posture, biological sex, application, exposure time.
- Lack of unified or standard methods to measure cybersickness.
  - A combination of physiological and subjective evaluations.
- Cybersickness has not been broadly explored in AR.
  - See through HMDs report low impact on generating cybersickness.

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CONCLUSION

Acknowledgments

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For more info about the project: https://a.bth.se/viatech-synergy/