Output Devices

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Based on material by Dieter Schmalstieg, Oliver Bimber and Skip Rizzo
Human Sensory Perception

- Vision ~ 70%
- Hearing ~ 20%
- Smelling ~ 5%
- Tasting ~ 4%
- Touch/haptic perception ~ 1%

In „The Cinema of the Future“, Morton Heilig, 1955, p. 247
Display Hardware

- Visual Displays
- Auditory Displays
- Olfactory Displays
- „Taste Display“
- Haptic & Tactile Displays
Immersion

“suspense of disbelief”
Suspension of disbelief is a willingness of a reader or viewer to suspend his or her critical faculties to the extent of ignoring minor inconsistencies so as to enjoy a work of fiction.

• Immersion into a convincing simulation of reality
• Presentation of the artificial reality is done by stimulating human senses
• Stimulation through Output Devices
Classification by Immersion

• Desktop Virtual Reality
  – = “Window on World” system
  – Conventional screen + 3D graphics

• Fishtank Virtual Reality
  – Tracking
  – Stereo (shutter glasses)

• Semi-immersive
  – CAVE, Workbench, large stereo screens

• Full Immersion
  – HMD, BOOM, VRD
  – options: audio, haptic interface
Visual Displays
Visual Display Characteristics

• Field of View (FOV), Field of Regard
  – Human FOV ~200°
• Spatial Resolution (dpi)
• Screen Geometry (rect., hemispherical…)
• Light Transfer Mechanism
  – Front/back projection, direct laser->retina
• Refresh Rate (Hz)
• Ergonomics
Depth Cues: How to see in 3D (1)

• Monocular static cues
  – Relative size
  – Height relative to the horizon
  – Occlusion (strongest)
  – Linear perspective
  – Shadows
  – Lightning & Aerial perspective
    • Bluish and hazy -> further away
  – Texture gradient
    • More texture detail -> closer
Depth Cues: How to see in 3D (2)

- Oculomotor Cues
  - Derived from muscular tension
  - Accommodation: Change of eye focal length
  - Convergence: eyes looking inwards

The eye accommodates for close vision by tightening the ciliary muscles, allowing the pliable crystalline lens to become more rounded.

Light rays from distant objects are nearly parallel and don't need as much refraction to bring them to a focus.

Light rays from close objects diverge and require more refraction for focusing.
Depth Cues: How to see in 3D (3)

• Motion parallax
  – Closer objects move faster
  – Very strong cue (esp. for far objects)

• Binocular Disparity/Parallax
  – “shift” in left/right images

• Problem with stereo displays: Cue mismatch
3D (stereo) viewing - Historical

- 1838 – Wheatstone stereoscope
Stereo Principles:
Active vs. Passive Stereo

- **Active stereo:**
  active switching
e.g. shutter glasses

- **Passive stereo:**
e.g. anaglyph stereo (red/blue), polarized filters, infinitec
Active Stereo: Shuttering

Shutter Glasses

Left Eye Image

Right Eye Image
LCD Shutter Glasses

- Monitors with high refresh rate e.g. 120Hz - >60Hz per eye
- show stereo image pairs sequentially
- monitor and eye glass are synchronized
- every eye sees “its” image

Nvidia GeForce 3D Vision glasses

NVIDIA 3D Vision Kit + 3D Vision-Ready Display + Compatible NVIDIA Graphics Card + PC with Microsoft Windows Vista or Windows 7
Stereo Monitor - Advantages

• Least expensive in terms of additional hardware over other output devices
• Allows usage of many input devices
• Good resolution
• User can take advantage of keyboard and mouse
Stereo Monitor - Disadvantages

• Not very immersive
• Users cannot move around freely
• Does not take advantage of peripheral vision
• Ghosting
• Occlusions can avoid IR contact between emitter – glasses -> no shuttering
Passive Stereo: Polarization

- Polarization filters create „different“ images for left and right eye
- Light is an electro-magnetic wave with
  - Amplitude (intensity)
  - Wave-length (color: visible light 380nm – 750nm)
  - Phase
Polarization

• Use two projectors
  – Left: vertical filter in front of the lens
  – Right: horizontal filter in front of the lens

• Wear glasses with polarization filters
  – Left eye: vertical
  – Right eye: horizontal
Figure 2.4. Polarization of light: only light waves with a specific orientation pass through the filter.
Polarization glasses

- Very cheap, paper + plastic foil
- Trick: use +/-45° -> no wrong side wearing

Polarization plane +/-45°
Polarization

• Linear polarization
  – Can’t tilt head
  – Little ghosting

• Circular polarization
  – More involved physics
  – Principle: counter clockwise / clockwise
  – Allows arbitrary head orientations
  – In general more ghosting than linear polarization
Wellenlängenmultiplex
Visualisierungssysteme

- Interferenzfiltertechnik (Infitec)
Stereoscopic Displays Today - Overview

- **Goggle Bound Displays**
  - Head-Attached Displays
    - Head-Mounted Displays
    - Boom-like Displays
    - Retinal Displays
    - Head-Mounted Projectors
  - Spatial Displays
    - Projection Displays
    - Desktop Configurations
      - Surround Screen Displays
      - Embedded Screen Displays
      - CAVEs
      - Domes
      - Panoramic Displays
      - Workbenches
      - Walls
      - Oblique Screens
      - Transparent Projection Screens
  - Desktop Configurations

- **Autostereoscopic Displays**
  - Re-Imaging Displays
    - Pepper’s Ghost Configurations
  - Volumetric Displays
    - Solid-State Displays
  - Multi-planar Displays
  - Varifocal Displays
  - Parallax Displays
    - Parallax Barrier Displays
    - Lenticular Displays
  - Holographic Displays
    - Electro-holographic Displays
    - Desktop Monitors
    - Reach-In Systems
Head Mounted Displays

Early prototype
Head Mounted Displays (HMDs)
1968: Sutherland’s 1st HMD

- Hidden-line graphics
- Mechanical tracking
- See-through HMD
Head Mounted Display (HMD)

- Device has one or two screens (e.g. LCD, OLED) plus special optics in front of the users eyes
- Provides a stereoscopic view that moves relative to the user
- 2 versions:
  - See-through or
  - User cannot naturally see the real world

Sony Glasstron (1997-2002): LCD display, Resolution: SVGA (832×624 pixels) FOV: 30 × 22 degrees Weight: 120 grams
See-through HMDs

• 2 Types:
  – Optical see-through
  – Video see-through

• Used in Augmented/Mixed Reality Applications
HMD - Stereo Transmission Principle: 3 Types

- **Line Interleaved Stereo**
- **Field Sequential**
- **Side-by-Side Stereo**

Sometimes: Top/Bottom
On/Off-Axis Projection

glPerspective \rightarrow \textbf{On-Axis}

Correct Way

glFrustum \rightarrow \textbf{Off-Axis}
Actual Costs (before 2012)

“Near Eye Immersive Display Systems”

$24,000

$2,900

$2,900

$10,000

$1,800

$600

$500-2,000

$10,000

$500-2,000

$20,000

(Trivisio)
Head Mounted Displays (2006-)
eMAGiN, Inc.

Sony HMD (HMZ T1/T2), 2011/12
800 EUR; 1280x720 OLED

$1500 w/ 3DOF Tracking
Organic Light-Emitting Diodes (OLEDs)

- No backlight necessary -> very thin
- Deep black levels
- Very high contrast
- Low power consumption
Oculus Rift

- Stereoscopic
- FOV: 100° diagonal
- Weight: 470 grams
- Resolution: 2 AMOLED 1080x1200 per eye @ 90 Hz
- Price ~450 EUR
- Inertial Tracker built in
- Precise IR optical tracking
- Low-persistence display (2ms)
- Adjustable lens spacing from 58 to 72 millimeters
HTC Vive Pro

• FOV: ~110° diagonal
• Weight: 555 grams
• Price ~1400 EUR
• Controllers included
• Inertial Tracker built in
• 2 cameras built in (see-through & depth)
• Resolution: 1440x1600 per eye @ 90 Hz
• Highly precise and fast Lighthouse Steam VR Tracking 2.0
  – Standard: Room scale tracking – max 10x10 meters
  – Theoretically large scale tracking up to 16 base stations
• Adjustable IPD; Lens distance adjustment
• Integrated Microphones & Headphones
HTC Vive Pro Eye & Wireless

• Wireless module available
• Pro Eye includes eye tracker
  – 120Hz binocular
  – gaze dir., pupil size, pupil pos., eye openness

Vive Cosmos (2019)
• Integrated SLAM Tracking (Lighthouse extension)
• 1440x1700 px per eye (LCD – higher px density)
Valve Index

- 130° FOV
- 1440x1600 (per eye)
- 120 Hz (with experimental 144 Hz mode)
- LCD display with high pixel density
- Lighthouse 2.0 tracking
- Knuckles controllers
Pimax

• 5K and 8K X versions
  – 8K X: 3,840 × 2,160 per eye, 75Hz
  – 5K: 2,560 × 1,440 per eye
• ~200° FOV
• Low persistence LCD (full RGB pixel matrix)
• Supports Lighthouse Tracking
• Integrated microphone
Stand-alone HMDs

• Onboard 6DoF SLAM tracking
  – Typically 4-6 front/side cameras
• Onboard processing (ARM chip) -> Wireless
  – Less computational power compared to wired HMDs
• Examples:
  – Oculus Quest: 1440 x 1600, 72Hz
  – HTC Vive Focus: 1440×1600, 75Hz
  – Pico Neo: 1440 × 1600 px
AR See-Through Wearable Displays

- Reflection on Curved Mirrors
- Waveguide-based

Diffractive Waveguide e.g. Nokia/Vuzix

Reflective Waveguide (Google, Epson)

Polarized Waveguide (Sony)
Magic Leap Optics

KGOnTech
Nov. 20, 2016

iFixit Picture August 23, 2018
(Labels by KGOnTech)

- waveguide
- entrance gratings
- "injection optics"
- polarizing beam splitter
- OmniVision LCOS microdisplay
- 6 LEDs (3 per color times 2 planes)
- LED light collimating lens
- compensation plate/film

Spatially Separate LED Illumination

Injection Optics

FIG. 6

US 2016/0327789

Green Eyepiece plane 2
Blue Eyepiece plane 2
Red Eyepiece plane 2

Green Eyepiece plane 1
Blue Eyepiece plane 1
Red Eyepiece plane 1
MS Hololens 2

- Small screen, ~52° FOV
- Resolution: ~2K per eye
- Ergonomics improved over Hololens 1
- Excellent SLAM tracking using 4 cameras
- Depth camera, IMU, HD video cam, 5 mics
- Stand alone unit
- Windows 10
- Eye-tracking included
Future: Near-Eye Light-Field Display

- Micro-Lenses (Nvidia) or Stacked LCDs
- Slim Design
- Focus change possible
- Small resolution in case of Micro-Lenses
Accommodation-invariant Computational Near-eye Displays
HMD - Properties

• Image:
  – FOV (Field of View)
  – Resolution
  – Fully immersive vs. see through
  – (Mono) vs. Stereo

• Ergonomics
  – Weight & Cables
  – Hygiene
  – Wearability
  – Ruggedness

• Cost
• Support (Repairing, ...
HMDs - Advantages

• Provides an immersive experience by blocking out the real world (non-see-through)
• Easy to set up
• Does not restrict user from moving around in the real world (…cable length)
• Good quality HMD is now affordable
• Achieves good stereo quality
HMDs - Disadvantages

• Might have limited resolution and field of view (FOV)
  – Does not take advantage of peripheral vision
• Ergonomics: sometimes heavy, hot, uncomfortable
• No extended use: ~30-60min. Cybersickness (!!)
• AR HMDs have low FOV
• Non see-through:
  – Physical objects require graphical representation
  – Safety: Isolation and fear of real world events
• Hygiene
Projection Displays
Basic Display & Projection Technologies

• Vorlesung Display Technologien:
  – Display Technologien:
    video.tu-clausthal.de/vorlesungen/ipp/visu-ws0304/flash/visu-10122003a.html
  – http://video.tu-clausthal.de/vorlesungen/ipp/visu-ws0304/
Projection Technologies: CRT

- CRT (Cathode Ray Tube) Projectors

+ High refresh rates (>100Hz) – stereo capable
+ Relatively low cost
– Large and heavy devices, can implode
– Consume a lot of energy
Projection Technologies : LCD

- Liquid Crystal Display (LCD) Projectors
  - Individual grayscale LCD for each color
  - Pixel dimensions <50µm
  + Low cost
  - Poor contrast and black level
Projection Technologies: DLP

• Digital Light Processing (DLP)
• Fast switching of micro-mirrors (brightness, color)
• Uses information of several frames for artifact compensation -> delay
• High refresh rates possible (>120 Hz)
• Relatively low costs
CAVE (1)  “Computer Assisted Virtual Environment” ™

- Has 3 to 6 large screens
- Puts user in a room for visual immersion
- Usually driven by a single or group of powerful graphics engines – nowadays PC cluster
CAVE (2)
RAVE

“Reconfigurable Automatic Virtual Environment”
CAVE - Advantages

• Provides high resolution and large FOV
• Uses peripheral vision
• User only needs a pair of light weight shutter glasses for stereo viewing
• User has freedom to move about the device
• Has space to place props (cockpit etc.)
• Environment is not evasive
• Real and virtual objects can be mixed in the environment
• A group of people can inhabit the space simultaneously (only tracked user sees correct stereo)
CAVE - Disadvantages

- Very expensive (>200,000 EUR)
- Requires a large amount of physical space
- Projector calibration must be maintained
- Only 1-2 users can be head tracked
- Stereo viewing can be problematic
- No direct interaction possible
  - No “walking around” an object as with HMD
- Physical objects can get in the way of graphical objects
Curved Displays

- Cylindrical or hemipherical screen
- Requires distortion correction
- Common in industry
Vision Dome

Spherical Display

VisionStation
Tiled Projector Display

StubeRena
Gottfried Eibner, 2003
Multi-Projector Display

- Warp & Blend
  - Warp = Geometry Corrections
  - Blend = Intensity Adjustments
Multi-Projector Walls

- Active or passive stereo
- Multi-projector setup
- Overlap, Edge Blending
  - Partly Nvidia driver support
  - Warp & Blend can be done on GPU
Multi Screen Displays

How to synchronize multiple displays?
(1) Multiheaded Graphics
(2) Multiple workstations: Genlock/ Framelock

**Genlock:**

**Exact** synchronization of vertical synch (electron beam of CRT)
• Refreshes each pixel synchronously

**Framelock:**

Synchronizing frame buffer swap
• Begins redrawing at the same time
Workbench / Projection / Touch - Table

Responsive Workbench, Holobench, Virtual Table...

- Technology similar to CAVE but one display (two at most)
- Can be a desk or a large single display (I.e. PowerWall)
- Traditionally a table top metaphor

IR Controllers
CRT Projector
Mirror
Tilting mechanism
Workbench - Properties

- High resolution
- Intuitive display for certain apps.
- Allows table-top placement of props
- Can be shared by several users
- Pen-based / Touch input possible
- Large FOV
Two User Workbench

- 4-way interleaving
- Problems
  - Reduced brightness
  - Cross talk
  - Refresh rates
Multi-user Approaches

- **Private screens**
  - Individual screen(s) / frame-buffer(s) per user / HMD for each

- **Frame interleaving**
  - Users share the same screen(s). Images rendered into individual frame-buffers displayed time-sequential. Special glasses separate images.

- **Screen partitioning**
  - Images are separated by additional optics.
Current Augmented Reality Displays
Pico Projectors

• Low brightness <800 lumens
• Max. 1280x800 resolution
• Image size max. 2.5m diagonal
• Projection distance max. 2.5m

Laser Projectors
  – E.g. Extend3D Werklicht
Projected Environments

Oliver Bimber, 2005
Projected Environments

Bacardi Party Projection

Adidas 3D Mapping
Mobile Devices

- Smartphones & Tablets
- Input device = Output device
- Output
  - Augmented Video Frames
    - Overlay real & virtual content
    - 2D (sometimes 3D)
- Input data
  - Video Frame (extract structures & information)
  - Touch & Device Orientation
  - Gyroscope, Accelerometer, GPS ...
Current Smartphone Specs

• Example: Samsung Galaxy S8 (Apr ‘17)
  – 2.3 GHz quad core CPU (Qualcomm Snapdragon 835) + quad-core 1.7 Ghz
  – 4 GB RAM, 64 GB storage
  – GPU: Adreno 540
  – 2960 x 1440 pixels, 5.8” Super AMOLED display
  – 12MP rear cam, 8MP front, 4K video capture, HDR
  – Sensors: Accelerometer, gyroscope, proximity, compass, barometer, heart rate, SpO2, Fingerprint
  – LTE/HSPA, WiFi a/b/g/n/ac, NFC, Bluetooth 5.0
  – GPS, Galileo, Glonass, BeiDou
  – Android 7
Spatial See-through Displays: Virtual Showcase

- Projection-based AR
- Special purpose display for museums
- Real and virtual images or objects are merged
- Max. 3 users
Transparent Displays

• Various Vendors
• Useful for AR applications
Auto-stereoscopic Display Technologies

- Stereo without glasses
- Types
  - Re-Imaging
  - Lenticular
  - Volumetric
  - Holographic

Figure 2.17. Examples of common real-image display configurations using one or two concave mirrors.
Lenticular 3D Displays

- Works without glasses!
- Various companies
- Some require/offer multiple views (up to 48)
- Others provide head tracking
Looking Glass

8 inch or 15 inch; 4K at 60Hz
only horizontal parallax, 45 views
40-50° view cone

45 unique views of a 3D scene are captured on a computer at 60 FPS. These dozens of views are encoded into a video signal that is sent via HDMI to the Looking Glass®. The Looking Glass optics decode the video signal into a full-color, superstereoscopic three-dimensional scene that multiple people can view and interact with. All without the need for VR or AR headgear.

Traces
Provides front and back depth cues

Optical Film
Sharpen subpixels

LCD
Displays 45 unique interlaced views of a 3D scene at 60fps

Dimensions
8.2" x 3.7" x 6.1" (L x W x H)
20.9cm x 9.3cm x 15.4cm (L x W x H)

Weight
4.8 lb / 2.2kg
Volumetric Displays

• 2 Types:
  – Swept volume: Plane or helical surface
  – Stack of planes

• LightSpace Technologies: DepthCube
  – 20 slices, 50fps, 1024x768x20
Volumetric LED Displays

- 48*96*192cm
- 40 mm pixels pitch
- 12*24*48 = 13824 LEDs
- SD Card controller
- 200 – 4200 Watt

Seekway 3D LED Cube
Volumetric Displays

- **Perspecta3D**
  - 1024x768x3 digital projector, 198 images/slices, 900rpm

- **Felix3D**
Holographic Displays

- Diffraction patterns encoding both amplitude and phase information of the light waves coming from a three dimensional object or scene
- Capable of reproducing these object light waves when illuminated with coherent light like lasers
- Up to now: photographic film emulsions and lasers used
- New development: Holografika
Figure 2.19. Optical holographic recording and reconstruction (example of a transmission hologram). (Image reprinted from [18] © IEEE.)
Holographic Displays

Figure 2.19. Optical holographic recording and reconstruction (example of a transmission hologram). (Image reprinted from [18] © IEEE.)
Tensor Displays

Compressive Light Field Synthesis using

- Multilayer Displays with
- Directional Backlighting
The Future...?

Laser Plasma

SolidFelix

Transparent Display

Foldable Displays
Auditory Output

• Main Uses
  – Localization: how to create spatialized sound
    • 3D Sound Sampling; Auralization
  – Sonification: communicate information
  – Ambient effects: realism
  – Sensory Substitution
  – Annotation and help (speech)
• Many different types of setups
• If used properly can be a powerful tool
• Tells user where to look
Olfactory Displays – Scent

- Sense of smell (or olfaction) is a primal chemical sense for humans. Impact on the central nervous system and hormone balance.
- Smell can influence mood, memory, emotions, social behavior, mate choice.
- Scents can e.g., reduce stress, enhance concentration or act as stimulants.
- Smell is more closely linked with memory than any other sense.
- Smell cannot be synthesized by single components!
  - Typically 100s/1000s of smell molecules involved in one smell.
Sniffman

Olorama
12 smells wireless aromatizing device

Scent Cannon
Taste

• Research on taste perception started in 1500s
• Taste is 80% smell
• 5 basic tastes. The chemical sensation is synthesized from 5 elements of basic taste:
  – sweet, sour, bitter, salty, and umami

• Food Simulator: A Haptic Interface for Biting
  – Simulates biting force

Hiroo Iwata, University of Tsukuba, Japan
Hiroaki Yano, Takahiro Uemura, Tetsuro Moriya
Flavour

• Flavour does not travel well
  – Raki tastes GREAT in Crete
  – Not so good elsewhere!

• It’s all about context
  – Where, with whom, preconditioning, etc
Haptics

- Greek: Hapthai = sense of touch
- Haptics
  - Touch/tactile feedback
    - Relies on sensors in and close to the skin
    - Most sensors are on the hand
    - Conveys information about contact surface
      - Geometry
      - Roughness
      - Slippage
      - Temperature
    - Does not actively resist user contact motion
    - Easier to implement than force feedback
  - Force feedback
Tactile Brush

- Stroking Sensations on skin
- Vibrotactile Array
  - velocity of between 1–10 cm/s
  - Produces feeling of linear motion
State of the Art (1)

Traditional Haptic Devices

1-Point Touch; Exoskeleton; Feeling Vibrations
Force Feedback

- Relies on human sensors on muscle tendons and bones/joints
- Conveys information
  - contact surface
  - Object weight
  - Inertia
- Actively resist user contact motion
- More difficult to implement than touch feedback
- No commercial products until mid 90s
CyberTouch Glove

6 individually controlled vibrotactile actuators

0-125 Hz frequency
1.2 N amplitude at 125 Hz
CyberGrasp Force Feedback Glove

Exoskeleton over CyberGlove

Cables and pulleys

12 N/finger (continuous?); Weight 350 grams; remote electrical actuators in a control box.
State of the Art (2)

Room-Scale Haptics – Traditional Devices on Mobile Platforms
State of the Art (3)

Haptics with Props
State of the Art at TU Wien

Hands-Free Haptic Interaction

Vonach E., Gatterer C., Kaufmann H.
Next Step:
Robotnik KAIROS Cobot
VR Interface Problems

- No Moore’s Law in the area of HMDs and other quality peripherals
- Need Cost/Benefit Proofs!
- Limited Awareness/Unrealistic Expectations
- (Aftereffects Lawsuit Potential)
- Ethical Challenges
# Cost-Benefit Analysis Summary

*Courtesy of Bob Stone*

<table>
<thead>
<tr>
<th>Item</th>
<th>Number of Real Rounds Fired or Aircraft Hours at HMS CAMBRIDGE in a typical pre-closure year*</th>
<th>Costs per real round or per aircraft hour, inclusive of VAT</th>
<th>Totals SAVED Through Simulator Introduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>30mm MSI</td>
<td>13,320 rounds (111 students x 120 rounds each)</td>
<td>$78 (£50)</td>
<td>$1.03 million (£666,000)</td>
</tr>
<tr>
<td>20mm GAM BO</td>
<td>26,160 rounds (218 students x 120 rounds each)</td>
<td>$50 (£32)</td>
<td>$1.3 million (£837,120)</td>
</tr>
<tr>
<td>Falcon 20 Aircraft</td>
<td>384 hours</td>
<td>$7666 (£4936)</td>
<td>$2.95 million (£1.9 million)</td>
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<table>
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<tr>
<th>Totals</th>
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<td>$5.3 million (£3.4 million)</td>
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The Interface Challenge
The Interface Challenge

- **Naturalism**: make VE & interaction work exactly like real world.
- **Magic**: give user new abilities
  - Perceptual
  - Physical
  - Cognitive
Interface Tools: Can we foster naturalistic interaction and do we need to?

“I have a 300 MHz computer...with 10 MHz fingers.”
Japanese Karakuri Horse
The Interface Challenge

• Will the target users be able to learn to navigate in and interact with the environment in an effective manner?

Universal Interaction Tasks

- Navigation
  - Travel - motor component
  - Wayfinding - cognitive component
- Selection
- Manipulation
- System control
The Interface Challenge

- Will the **cognitive overhead** required to use the interface distract users from the intended tasks and goals?
Barnett et al. (Boeing; 2000): “As a result of these* unique features of the VR, four of the participants commented that they focused more on interfacing with the VR than with learning the task”

* Poor field of view, poor depth perception, object distortions, object manipulation
The Interface Challenge

Cost vs. Precision?

$100 Gaming Glove? vs. $5000 Wireless Glove?
Consider Human Factors!

Most people are not exited about HMDs & Foot-Mounted Trackers...
General Guidelines for Choosing I/O

- Money is a big factor
- Think about what interaction techniques are required
- Choosing input device restricts the choice of output device
- Choosing output device restricts the choice of input device
- Application design depends on input+output devices and vice versa
- Creativity is important

There is not a single ideal solution for all applications! Know the possibilities!
When is a VE effective?

• Users’ goals are realized
• User tasks done better, easier, or faster
• Users are not frustrated
• Users are not uncomfortable
• And there is some measurable gain in targeted real world performance
Literature


Using the latest in medical technology, modern podiatrists are able to study Phil's ingrown toenail in virtual reality.