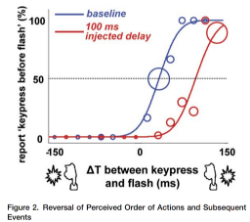
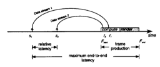
* VR Latency Paper
  + Display Lag
    - Frame Latency
      * Very Dependant on Display Technology
        + Between 15 and 140 ms (Waltemate…Botsch)
      * Dependent on graphics architectures
        + graphics clusters add lag (Walemate…Botsch)
      * Dependent on actual graphics
        + Walemate…Botsch
    - Frame Transition Shape
  + Minimum Requirements for VR
    - No standards exist
      * Waltemate…Botsch
    - Some Minimum acceptable
      * (cited in Waltemate…Botsch)
        + 1 Second (Shneiderman, 1984)
        + below 120ms network lags unnoticed (Mauve…2004)
        + 200ms increases error rates in coordination task (Gutwin, 2002)
        + Higher latencies produce a “move and wait” movement strategy (Park…1999) (Sheridan & Ferrell, 1963; cited in Hill…Ellis, 2004)

Jitter had larger impact than latency

* + - * + Trained users can detect latency of ~15ms in an HMD (Mania…2003)
        + Motor prediction can be used to adapt to lag (Keetels & Vroomen 2012; Rohde & Ernst 2012; Heron…2009)
        + 150ms for video game controls (Jörg…2012)
        + Decreasing latency from 90ms to 50ms increases sense of presence in virtual environments (Meehan…2003)
        + Perofrmance on Fitt’s tapping task reduces with lags of 75ms or higher (Mackenzie & Ware, 1993)

Not much improvement in tapping task below 40-50ms, even without VR (Jota…2013)

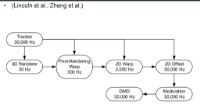
* + - * + 70ms lag affects performance in VR reaching task (Ware & Balakrishnan, 1994)
        + JND of 10-15msecs detectable in augmented reality (Ellis…Hill, 2004)
        + 8-20 ms of head-tracking latency in HMD (Ellis…Hill, 2004; Adelstein…Ellis, 2003; Mania…Hill, 2004; cited in Hill…Ellis, 2004)
        + 33 msecs latency in HMD (Jacoby…Ellis, 1996; cited in Hill…Ellis, 2004)
        + 50 msecs of latency in HMD (Ellis…Ehrlich, 1999; cited in Hill…Ellis, 2004)
        + Standard for FAA flight simulators is 150 ms (FAA, 1991; cited in Hill…Ellis, 2004)
      * Optimal somewhere around 40-70ms (Walemate…Botsch)
      * (Cited in Friston & Steed)
        + 17ms reduces presence (Adelstein…Ellis, 2003)
        + latency effect even <17ms (Jerald…Whitton, 2008)
        + Responsible for simulator sicnkess (Buker…Deaton, 2012)
      * Found JND of 5-19msecs of added latency (Mania…Hill, 2004)
      * 150-250 msecs for information for pilots to purforming landing procedures (HUDs) (Bailey…Kramer, 2005)
        + Reccomends 20msecs total latency, though, to meet theoretical requements and pilots’ feedback
    - latency adaptation
      * Users cannot adapt to latency jitter
        + Attempts to measure jitter use clocks from devices (Stauffert…Latoschik, 2016) (2 papers by same author, same year)
      * (button press - light relationship): consistent lag can lead to a recalibration of temporal order judgments. (Stetson…Eagleman, 2006)
      * 
  + Effects of Latency
    - Buker…Deaton, 2012
    - (Jerald…Whitton, 2008)
    - MacKenzie…Ware, 1993)
    - Meehan…Brooks, 2003)
    - Slater…Sanchez-Vives
    - (Zimmons…Panter, 2003)
    - In AR szstems, mismatch in latency between real-world and VR scenes decreases performance and decreases self-reports of precision and ease of use by participants–best to lag real stimuli (Nabiyouni…Höllerer, 2017)
      * latency effects registration of virtual images (Azuma…2001)
    - Simulator Sickness Questionaire (SSQ) was modified from Motion Sickness Questionnaire through factor analysis. (Kennedy & Lane, 1993)
      * Items: Discomfort, Fatigue, Headache, Eyestrain, Difficultry focusing, increased salivation, sweating, nausea, difficulty concentratring, fullness of head, blurred vision, dizziness (eyes open vs eyes closed), vertigo, stomach awareness, and burping
        + Factor N (Nausea): Nausea, discomfort, difficulty concentrating, burping, stomach awareness
        + Factor O (Oculomotor): discomfort, fatigue, headache, eyestrain, difficulty focusing/concentrating, blurred vision
        + Factor D (Disorientation): Dizziness, Difficulty focusing, Nausea, Vertigo
      * Found elimination of sicnkness scores after 6 monthly “hops” in military flight simulator
        + Sickness decreased when 2-5 days were allowed between hops. Sickness remained in shorter and longer inter-hop periods
    - (Ellis…Adelstein, 1997)
    - Lowering latency increases sense of presence and higher physiological fear response to walking over virtual pits (Meehan…2003, cited in Mania…Hill, 2004)
    - Weber’s Law doesn’t hold for latency perception, so JND can’t be used to judge minimum latency detection level.(Ellies…1999ab, Adelstein…3003, cited in Mania…Hill, 2004)
  + Sources of Latency
    - (Jacobs…State, 1997). Methodologically describes the sources of latency and compares solutions
    - 
      * “Off-host delay”: time between occurance of physical event and its arrival on the host
      * “Computational Delay”: time while the system is computing the data
      * “Rendering Delay”: time while the graphics engine is generating the picture
      * “Display Delay”: Time between sending images to the display and the display actually showing them
        + VSync. while reducing render artifacts, introduces major delays (40-50msec) (Raaen & Kjellmo, 2015)
        + Solutions

2D Warping can also be done on low-powered integrated gpus on HMDs with a deferred-rendering quadmesh approach (Peek…Wünche, 2013)

Also can be done at the pixel-rendering level for CRT displays, to account for raster time during frame rendering (Olano…Bishop, 1995)

Predictive Warping, late in rendering pipeline, also helps (Friston, presentation on ultra-low-latency VR and the DataFlow Renderer)

Cites (Lincoln…) and (Zheng…Fuchs, 2014, “Frames considered harmful”) as great examples of this, which he calls “Cascaded Image Warping”



Physical mirrors also work for this purpose in video projector systems (Okumura…Ishikawa, 2012)

“Reflex HMD” : 2D distortion at the VRAM->display level (Kijima…Ojika, 2001)

Frameless rendering solves this problem (Friston, 2016)

3D warping with latest tracker info can also be done, although occulsion errors can degrade image quality a bit (Smit…Froehlich, 2009)

* + - * “Synchronization delay”: Time the data is waiting without being processed
      * “Frame-rate-induced delay”: time the delay ins’t updated, where the user sees and outdated image string.
        + “This delay can be considered a special case of synchronization delay between the display system and the human eye”
    - (Papadakis…Koutroulis)
      * “User-input device lag: the lag introduced from the communication between the tracking system and the VE application.”
      * “Application-dependent processing lag: the time required for the computation of the 3D model and depends on the complexity of the model and the application itself.”
      * “rendering lag: the time that passes until data sent from the VE application to the rendering hardware appears on a monitor or immersive display”
        + depends on the virtual scene and viewpoint of the scene
      * “synchronization lag: the total time that data is waiting during the necessary communication of involved input devices, in between the parallel processing stages of the VE application”
        + Adds unexpected latency, over the amount given by components (Hill…2004)
        + vsync

addds a frame of latency, but you can get around this by taking the v-sync singal from VGA and piping to parallel port for application (Hill…2004, cited in Papadakis…Koutroulis)

* + - * + Back-to-front buffer swapping

triple-buffering adds another frame lof latency

* + - * + “dynamic asynchrony”: between tracker and updates of graphics application

eliminated by doubling the signal freuqency to match the tracker. (Hill…2004)

* + - * + “static asynchrony”: idling time spent waiting for monitor to be ready

solved by just-in-time tracker polling (Hill…2004)

* + - * “frame-rate-induced lag:, resulting from the fact that data displayed progressively become out of date, while the display is not updated fast.”
        + “not considered as end-to-end latency”
        + but is important, because it’s perceived by users (Wloka 1995)

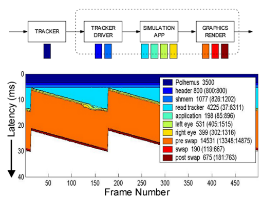
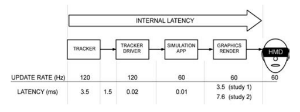
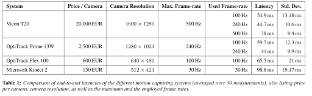
(Wloka 1995)

* + - * + Produces errors in head direction in head-tracked setups

(Mania…Hill, 2004)

(Stanney…,1998)

(Ellis et al. 2004)

* + - * + (Nick: low-persistance displays help with this)
    - (Hill…Ellis, 2004)
    - 
      * uses V-sync signal to offset the tracker in order to control the delay
    - (Mania…Hill, 2004)
    - 
  + VR Systems with Unreported Lag
    - VR-using studies should always report lag (Walemate…Botsch)
    - Smeddinck…2014: uses Kinect, so likely has >100ms lag, which is likely too high for study (cited in Walemate…Botsch)
  + VR Systems need Low Lag
    - Prediction model: Kalman filtering
      * Ballumiere (Miyafuji…Koike)
  + Tracking Lag
    - Table of IR Tracking Systems and measured lag (Waltemate…Botsch, 2015)
    - 
      * Note: Actually measured Total lag, not Tracking lag
  + Methods for Measuring VR Lag
    - % projected color (Ballumiere: Kiyafuji…Koike)
    - (Seen Cited in Chang16, paper 439)
      * Photodiodes+Oscilloscope+Servomotor (Papadakis…)
        + Manual reading from oscilloscope, no analysis
      * Virtual pendulum, fit sinusoidal function (Steed…)
        + used 500MHz camera
        + Could detect 11ms latencies

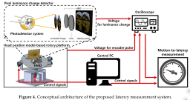
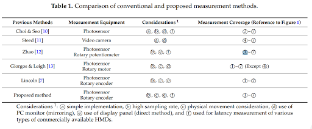
couldn’t get significant 3msec latencies, speculated as being from variations in latency of the system or the measurement technique

* + - * Two photodiodes on gradient images (Di Luca…)
        + differential approach Contains unkown latencies and overestimates latency
        + Uses soundcard to process data–higher than framerate resolution

but soundcards have high-pass filter. Thought that there was a 60Hz modulation of display, but not true for all displays

* + - * + 44KHz sampling rate
    - (Cited in Friston & Steed)
      * Measure device pin timing to see when dat was received (Miller & Bishop, 2002; Mine, 1993)
        + Using parallel port (Miller…McClain, 2003)
        + Directly measure hardware clock of each component of tracking system

(Adelstein…Ellis, 2003)

* + - * Photodiode on a pendulum, to measure time of passing through a light point and compare to another diode on a display (Mine…) , (Cited in Friston & Steed)
      * Measure Graphics command timing to get internal render delay (DirectX: Chen…Lei, 2011), (Cited in Friston & Steed)
      * Measured latency of trackers with different accelerations (Mehcnical arm) (Adelstein…Ellis, 2003), (Cited in Friston & Steed)
      * Manual frame counting techniqe (Roberts…), (Cited in Friston & Steed)
        + But has maximum timing resolution of 1 frame and inherent timeing ambiguity issues (Friston & Steed)
      * Continuous latency measurement of angular differnece between displays (Wu…Hoover, 2013), (Cited in Friston & Steed)
        + 1Khz camera
      * Measuring times of moving circles on a display, linking display and tracking systmem clocks (Sielhorst…Navab, 2007), (Cited in Friston & Steed)
    - “Automated Frame Counting” approach: virtual object that follows tracked object, use machine vision to measure latency (Friston & Steed) (Note: similar to what Rizwan and I did)
      * Compares to Sine-Fitting Method from (Steed, 2008)
        + finds 7msec, 12msec 99% CI accuracy lag estimation
      * Compares to (DiLuca, 2010)
        + Notes that display flickering and settings could affect measurements; reccomends turning certain settings on in order to get oscillations
      * Difficulties in lighting, complexities in scene, high data volume from high capture rates, can make frame counting inaccurate and difficult
        + Notes that (He…Sandin, 2000) used a grid to help with this, but that it took 10 hours to manually perform frame-counting
      * Relies on sensing motion, found that manual frame counting is time-consuming.
        + Similar performance as to compared to other techniques.
        + Found Stteed’s method to be easiest to use–reccommends that one instead of one listed in this paper.
    - The “Windhield Washer test”. User-reported visual slip magnitude from self-generated head rotations (Augmented Reality HMD in aircraft) (Bailey…Kramer, 2005)
    - (Potential additional papers)
      * Continuous latency measurement approach shows conflation between tracker error and latency jitter (Wu…Hoover, 2013; NOT READ BECAUSE OF PAYWALL)
      * Sielhorst…Navab, 2007
      * Mine, 1993
      * Miller…McClain, 2003)
      * Miller & Bishop, 2002
      * Gunn…Adcock, 2005)
      * Chen…Lei, 2011
      * Adelstein…Ellis, 2003)
      * (Adelstein…Ellis, 1996)
    - Photosensors connected to accelerometers with oscillloscope output, used for HMDs (Seo…Kang, 2017)
    - 
      * Oculus latency tester exists, but just tests the display latency (no head movement detection) and is limited to one HMD model.
      * Comparison of latency measurement methods
      * 
      * Uses robotic table for generating movement and getting movement timing of hmd
      * Found large changes in latency from randering load, from 43ms to 381ms
    - Movement Inputs
      * Subject-generated movements
        + Latency meter: just measures velocity and stop events of “center of brightness” of two synchronized cameras’ images (Miller & Bishop, 2002), (Cited in Friston & Steed)

works for all virtual environments, flexible

* + - * + light and sensor on a tripod facing a white wall (Raaen & Kjellmo, 2015)
        + automated frame counting (not named) on robotic surgery robot (Li…Li, 2017), tracking black bars on the master and slave robots

breaks down latencies to individual components

analyzes full timecourse of lag during a motion.

found latency measurement errors from: poor spatial calibration, wrong calculation, and high accelleration

Measured 150-170msecs error, produced distribution

* + - * Motorized Movements controlled by software
        + Robot moving HMD (Seo…Kang, 2017
        + Motorized swing arm (Adelstein…Ellis, 1996; paywalled)
      * Regular Movement Inputs
        + from pendulum

Tested magnetic-field Polhumus Isotrack tracking system (Liang…Green, 1991). Tracked a Pendulum with a video camera and displayed a timer on a display.

Spatial jitter also adds error to the virtual perception

Found large jitter for position data, low jitter for orientation jitter

They made two types of filters to minimize jitter without introducing too much lag

high order (8-10) filter for side-to-side head movements

low-order (2-3) filter for forward-back headmovements

low lag for position, high lag for orientation

They make a kalman filter for the orientation data

Lower lag when the application directly polled the tracker than when it continuously received data

reccomends a just-in-time approach

Steed, 2008

Oscilloscope comparing 3 signals. pendelum crossing LED/sensor,tracker position data, and brightness on display (Jacoby…1996, cited in Papadakis…Koutroulis, 2011)

Later, a swing arm motor instead of pendulum used

HMD on a pendulum, compared data to gradient stimulus on HMD display (Poster, Zhao…Jennings, 2017)

* + - * + spinning

Rotating Platform + External dispay + high-speed camera (Applie iPhone 6, 240fps) (Chang 16, paper 439)

phonograph turntable instead of pendulum (Swindells…Booth, 2000, cited in Papadakis…Koutroulis, 2011)

Oscilloscope compares signals: shaft encoder on motor rotating the tracker, and a photodiode on a computer monitor (Papadakis…Koutroulis, 2011)

Note: contains great history of latency measurement techniques

Need to directly measure monitor because it’s what the user sees–RGB signals alone don’t give the full latency info

Video data and photodiode info is less accurate than oscilloscope of digital signals

Note: congtains great description of a standard graphics pipeline

“The latency of the VE system is the sum of the completion times required for each of the consecutive processes in the pipeline to be processed.”

Continuously-measures brightness in digital oscilloscope (10kHz), transferred to PC via USB

Found that the device helped optimize latency in their system, cutting it in half

Note: pretty similar to our device

* + - Display Outputs
      * Color variation on screen to compare tracking systems (Hill…, 2009)
      * QR Codes on two monitors (Jansen & Bulterman)
      * Video records differences in lag between marker and the motion field of a grid. (He…Sandin, 2000)
      * 
        + 16ms precision
        + Took 5 hours to manually review the video data
      * light sensor on a tripod with HMD , with virtual scene changing from black to white, with oscilloscope linking sensor from real wall and screen brightness from virtual wall. (Raaen & Kjellmo, 2015)
        + 5-10 measurements per device
      * VGA cable’s RGB signals measured directly instead of using a photodiode. Also directly tapped timestamps of the application code to get a fuller latency profile (Hill…2004, cited in Papadakis…Koutroulis, 2011)