Latency, Jitter, and Dropouts in Human Pointing Performance

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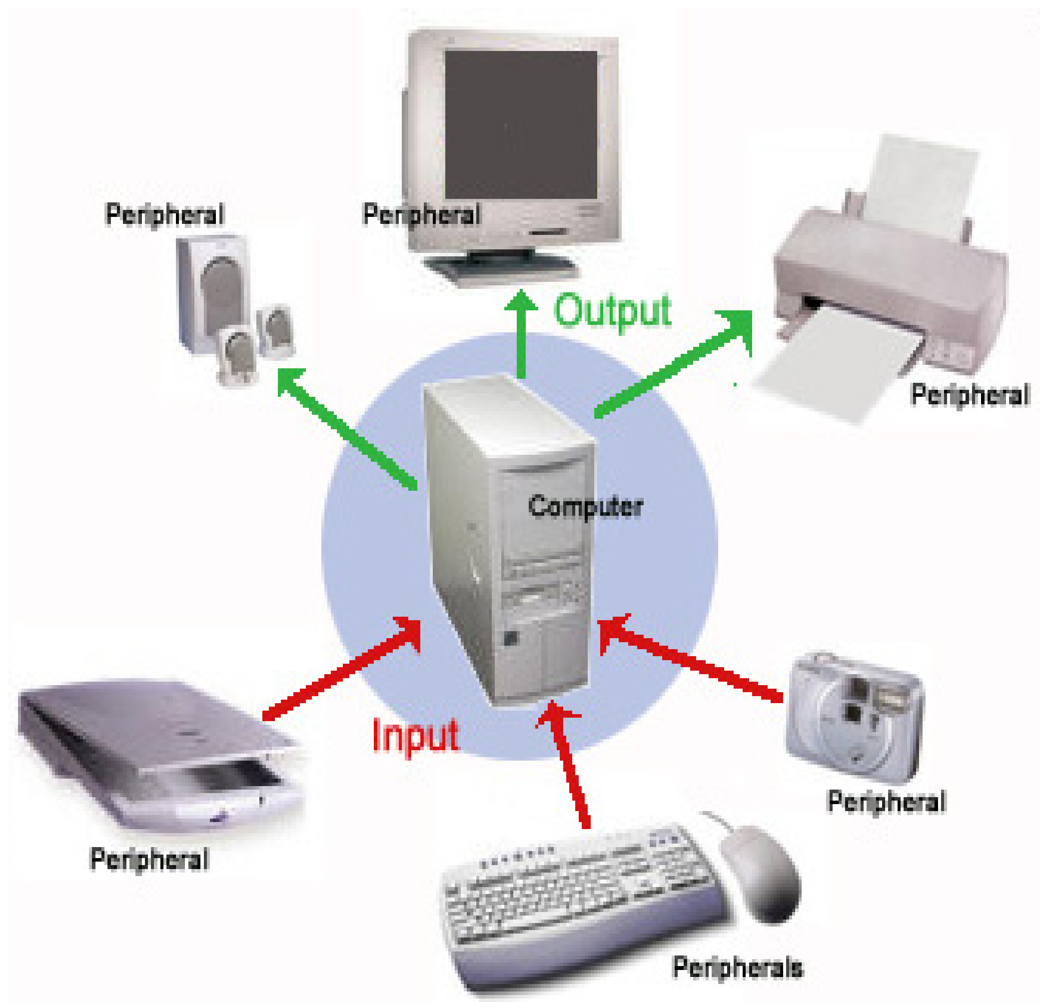
Computers

- Computers:
  - Process data
  - Require input
  - … and output



Computer Input

- Alphanumeric
  Keyboard, physical sliders/dials (numbers), Speech (text)
- Pointing
  Mouse, Touchpads, Trackballs, Pointing Sticks, Joysticks, Pen Input, Touch Screen, Light Pen, Digitizer, Graphics Tablet, Electronic Whiteboard
- Other
  Scanner, Microphone, Audio Capture Cards, Video Capture Cards, Pressure Pads…

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- Other

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Pointing Devices

- Also: eye-tracking, direct touch, hand gesture recognition, etc.

Factors Affecting Pointing

- Depend on underlying technology
  - Latency
    - Image processing delay
  - Latency jitter
    - Network latency variation
  - Dropouts
    - Lower reliability for video-based tracking
  - Spatial jitter
    - Hand tremor with laser pointer

Effect on Pointing Interaction

- All of these factors affect interaction
  - Reduce selection speed
  - Cause target misses
  - Decrease input device resolution
  - Induce fatigue

Latency in Computing Systems

- Time from when device physically moved, to time the corresponding update appears on screen
- Reduces performance
  - Drops in mouse throughput with added lag
  - Errors in 3D tracking
  - Simulator sickness in VR

Lag: Tracking and Measurement Technology Induced Delays

- Sample rate of sensors
  - Speed of sound in acoustic sensors
  - Video camera frame rates
- Noise processing
  - Processing-intensive, sometimes in time-domain
- Physics limitations
  - Inertia
  - Signal propagation

Lag: Network latencies

- propagation delay
  - Speed of light (2–3·10^8 m/s)
- transmission delay
  - Determined by rate
- processing delay
- routing delay
- retransmission and error-recovery delay

Lag: Computational Delays

- Input filtering
  - Noise, outliers, missing samples
- Input data transformations
  - simple mapping for touchpads
  - more complex for sonars and video systems
- Content processing
  - Re-layout of a document
  - Collision-detection, simulation algorithms in games
  - Drawing routines in computer graphics

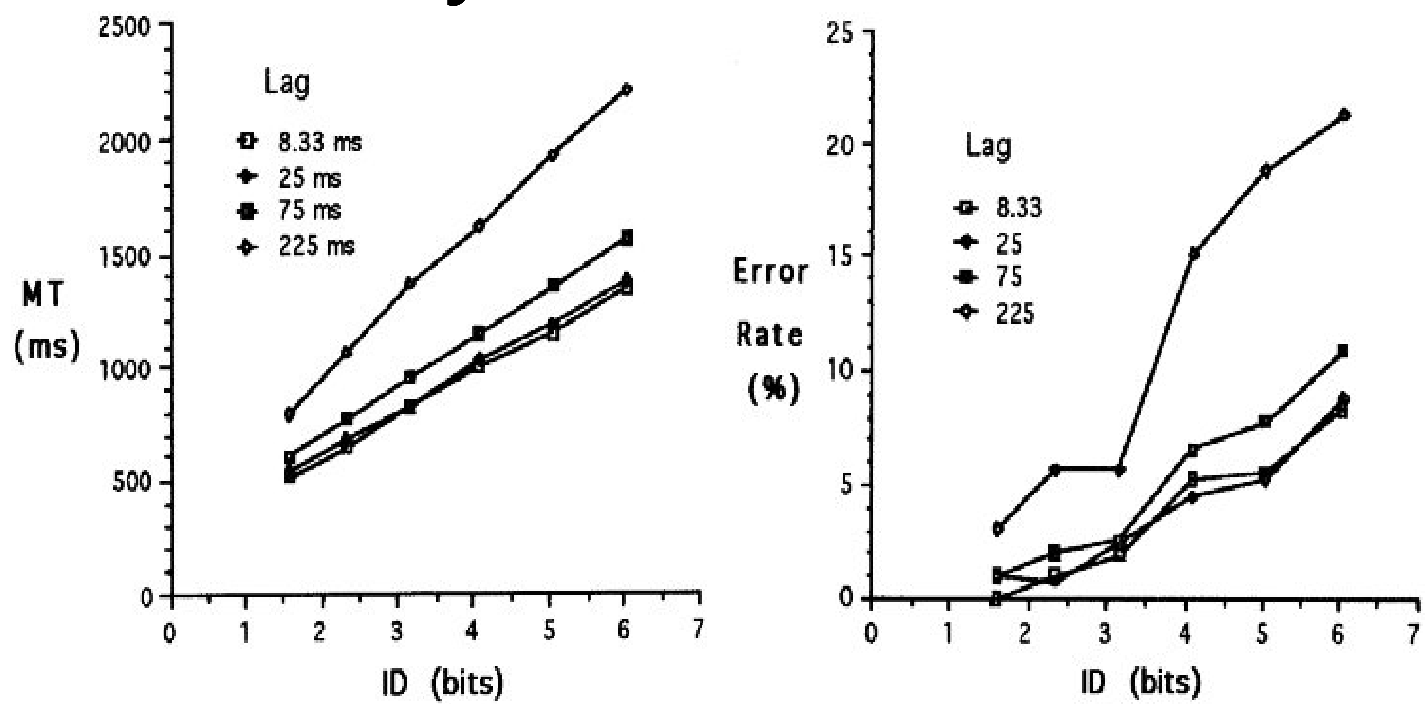
Lag: Display subsystem-induced delays

- Form image in memory / frame buffer
- Send that data to display device
- Display formed image
  - Some technologies are slow
    - IPS, DLP, E-Inc, any LCD when cold

Lag: Operating systems delays

- Processing is usually needed
  - Scheduler needs to be involved
- Time quanta
- Priorities

Human stimulus responses in context of latency



from Mackenzie and Ware (1993)

Latency Jitter in Computing Systems

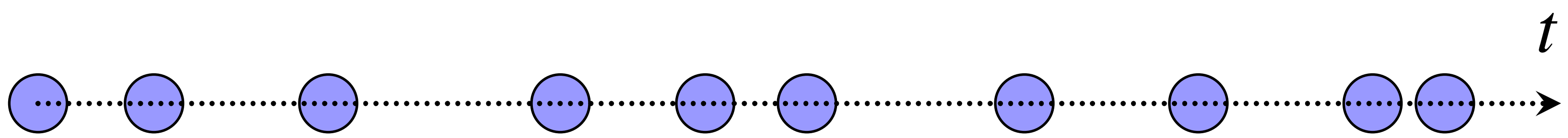
- – changes in lag with respect to time
- people can detect very small fluctuations in lag, likely as low as 16 ms
  [Ellis *et al*, 1999]
- well researched in electronics engineering
  - magnitudes of 1 ns almost irrelevant in HCI

Latency Jitter

- Fluctuations of latency with time
- E.g.,

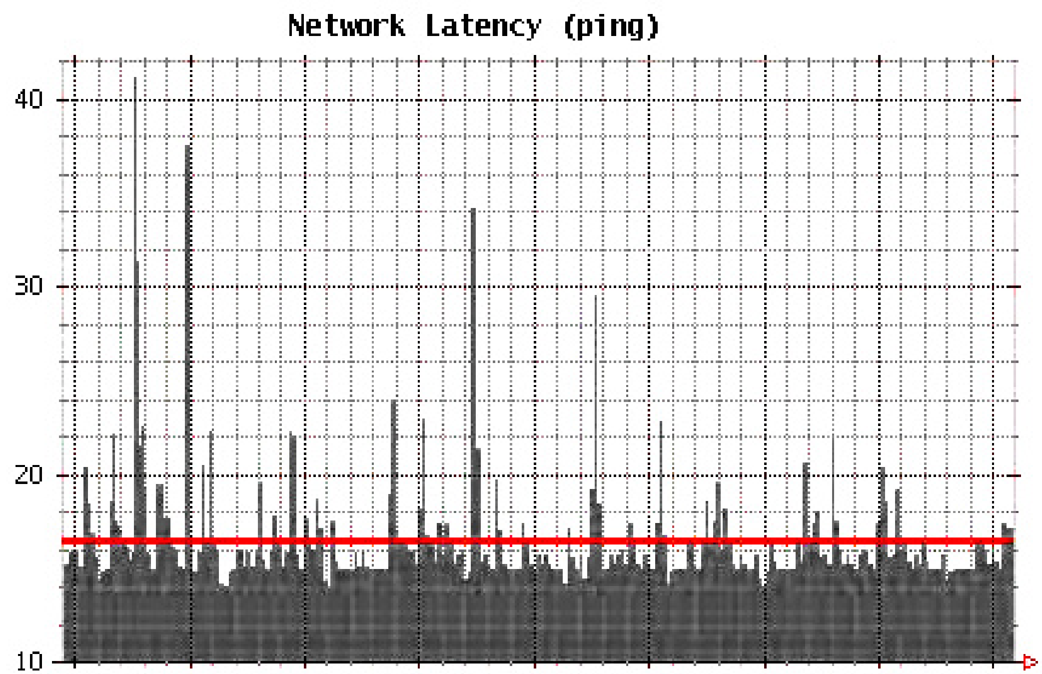
  Packet 1 is delayed by 18 ms, packet 2 – by 39 ms

  Cursor speeds up and slows down



Latency Jitter: Network Delays

- varying technologies, routing algorithms, and paths
- Varying network traffic conditions



Time Jitter: Processing Time Variations

- Running time: can depend on content
  - Detecting laser spots: **f(# of bright spots)**
- Incremental tracking algorithms
  - single missed image frame => multiple frames need to be accumulated before tracking stabilizes
- Tracking failures
  - Dropout?

Jitter due to OS Scheduling

- Pass data: input device -> device driver
- Result of device driver -> user application

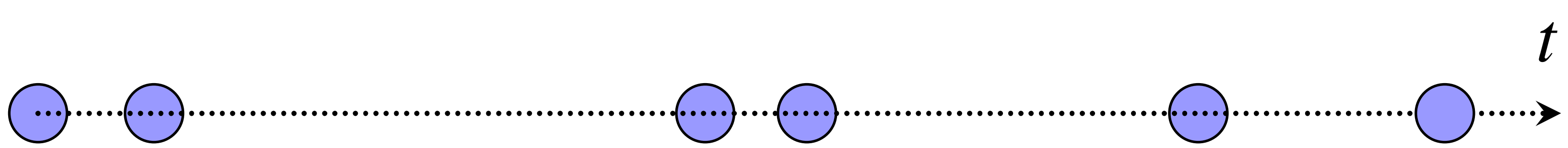
- Processes with higher priority may exist
  - Device drivers – priority over user applications
- No effective way to guarantee uniform scheduling delays

Dropouts in Tracking Devices

- Signal losses
  - Acoustic trackers affected by transient environmental sounds
  - Electromagnetic trackers stop working near ferromagnetics
  - Optical systems: obstructions, poor lighting, sensor noise, etc.
- Temporary signal loss -> *dropout*
  - During this time pointing is impossible
  - Cursor will "freeze" for a moment

Dropouts

- Some movement actions are lost
  - UDP packets, unreliable link
- Some actions are delayed by large amounts
  - Useless by the time they arrive
  - Extreme latency jitter, technically
- Cursor freezes in place and then jumps



Obstructions and Environmental Conditions

- "Natural" interaction vs. tracking reliability
  - hand gestures: fail if person turns back to camera
  - vision-based: not reliable in adverse lighting conditions
- Wireless links

Signal Attenuation

- Camera illuminating objects with infrared light and tracking them via retro-reflective markers [Natural point]
  - irradiance of objects is inversely proportional to a 2^{nd} power of distance
- Similar: wireless mouse

Spatial Jitter in Computing Systems

- noise in device signal
- hand tremor
- combination of both

- To observe spatial jitter
  - Immobilize a tracking device
  - observe reported positions
  - some devices have *additional* noise during movements
  - Hand jitter only exacerbates this problem

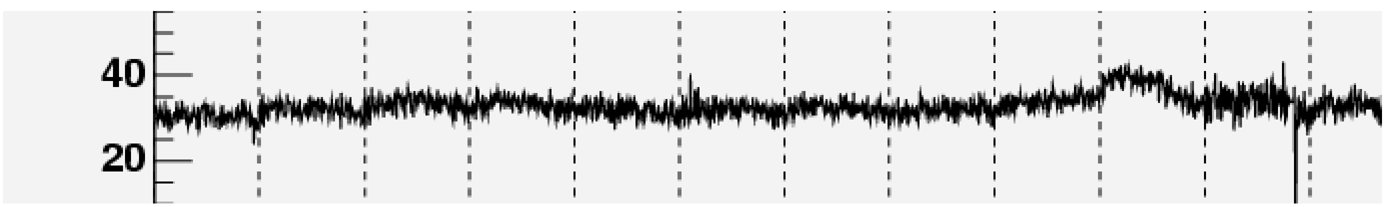
Spatial Jitter

- Some spatial offset from the norm

- E.g.,

  Move mouse along a straight line

  Cursor moves along a jagged path



Inaccuracy of tracking technologies

- measurement inaccuracy
- exacerbated by
  - higher temperatures (increases thermal noise and many physical parameters)
  - optical sensor size miniaturization
  - lower signal strengths in modern devices
  - drift in component parameters

Spatial Discreteness of workspace in digital domain

- When limited resolution trackers are used
  - Some points of workspace cannot be distinguished
  - Still a noticeable source of jitter

Hand tremor and environmental conditions

- Tremor occurs in every normal individual
  - heightened by strong emotion, physical exhaustion…
- Physical characteristics matter
  - E.g., certain laser pointer enclosures work better for manipulating a cursor [Myers *et al*., 2002]
- Mechanical Vibration
- Temperature

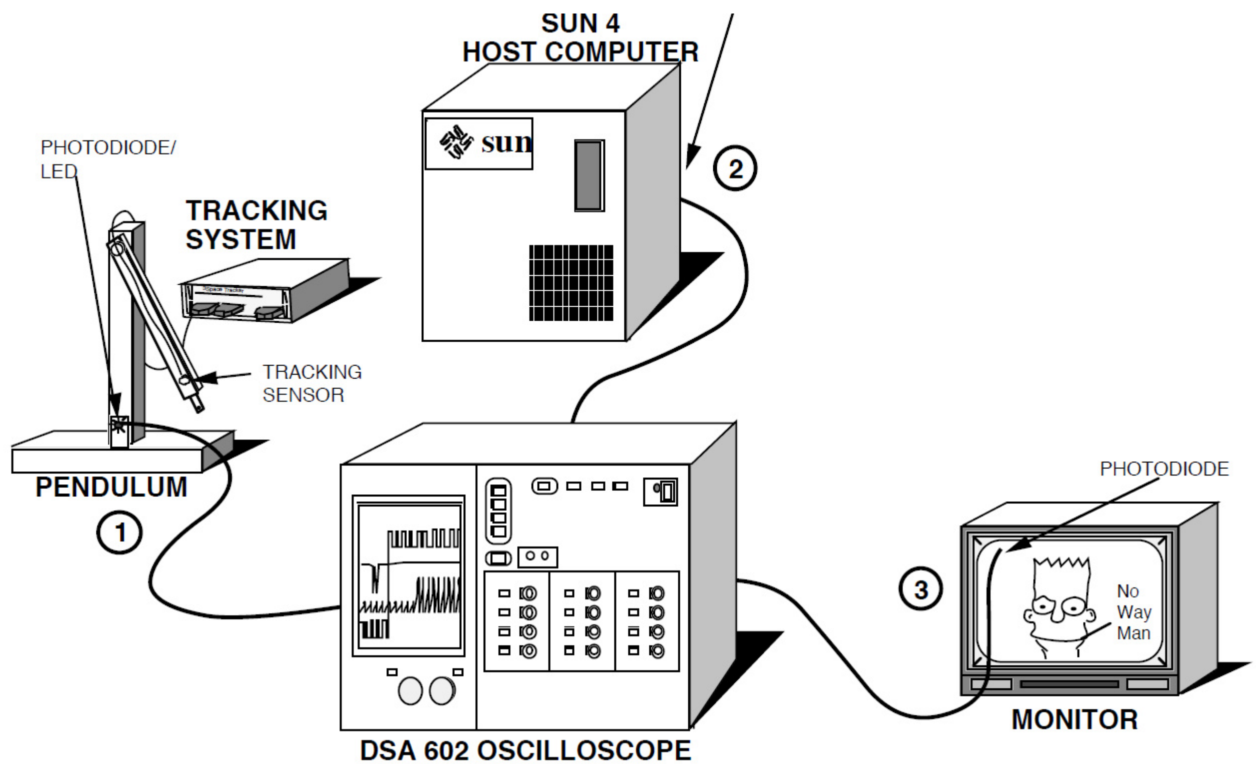
System Performance

Measuring System Performance

- End users evaluate devices subjectively
  - aesthetics, colour, convenience during use, brand logo…
  - Performance also a factor but diluted by other factors
  - cannot rely directly on end-user judgement
- Need to judge devices' performance objectively
- Ability to compare devices, models, and different algorithmic approaches for low-level processing
- How do we measure latency, latency jitter, spatial jitter, and dropouts?

Measuring Latency, Mine's Method

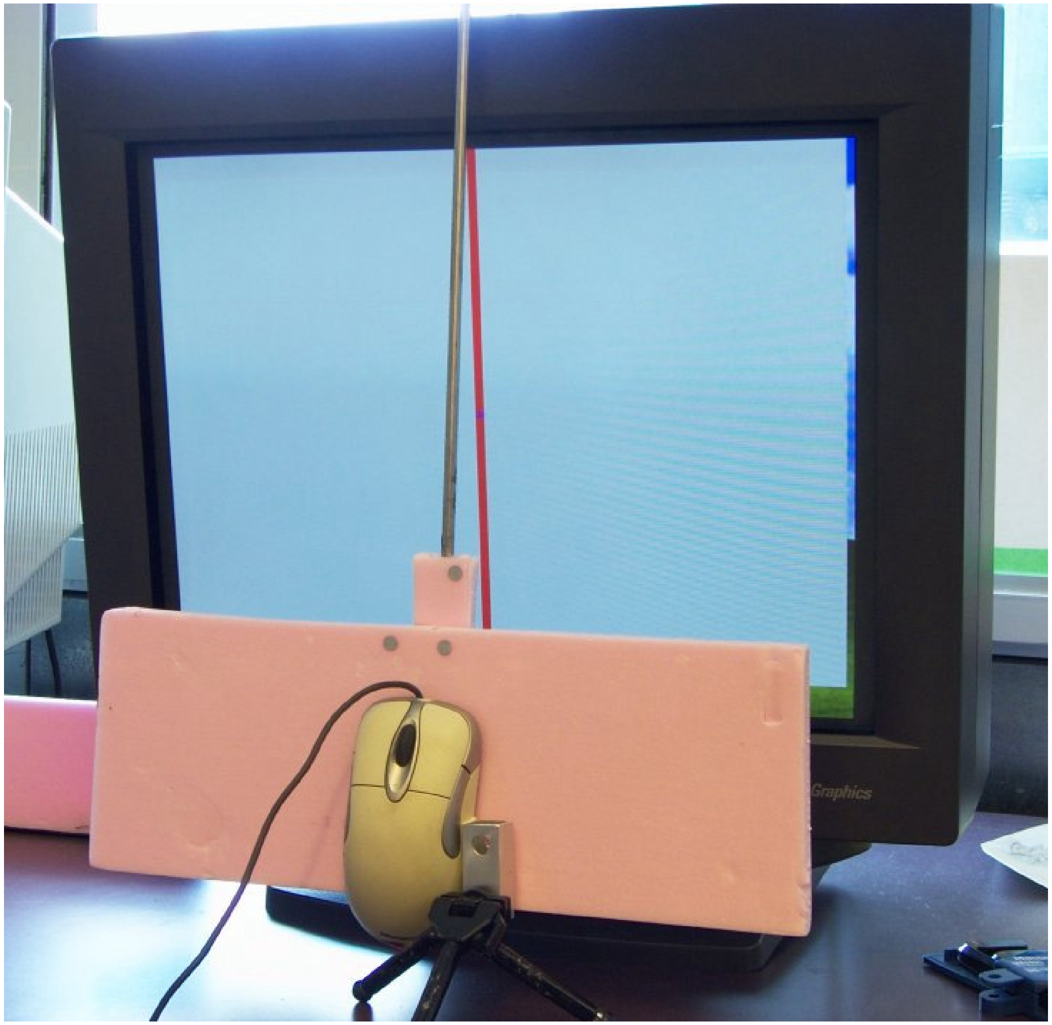
- difference between movement of pointing device and the perceived effect of such movement



Measuring Latency, Steed's Method

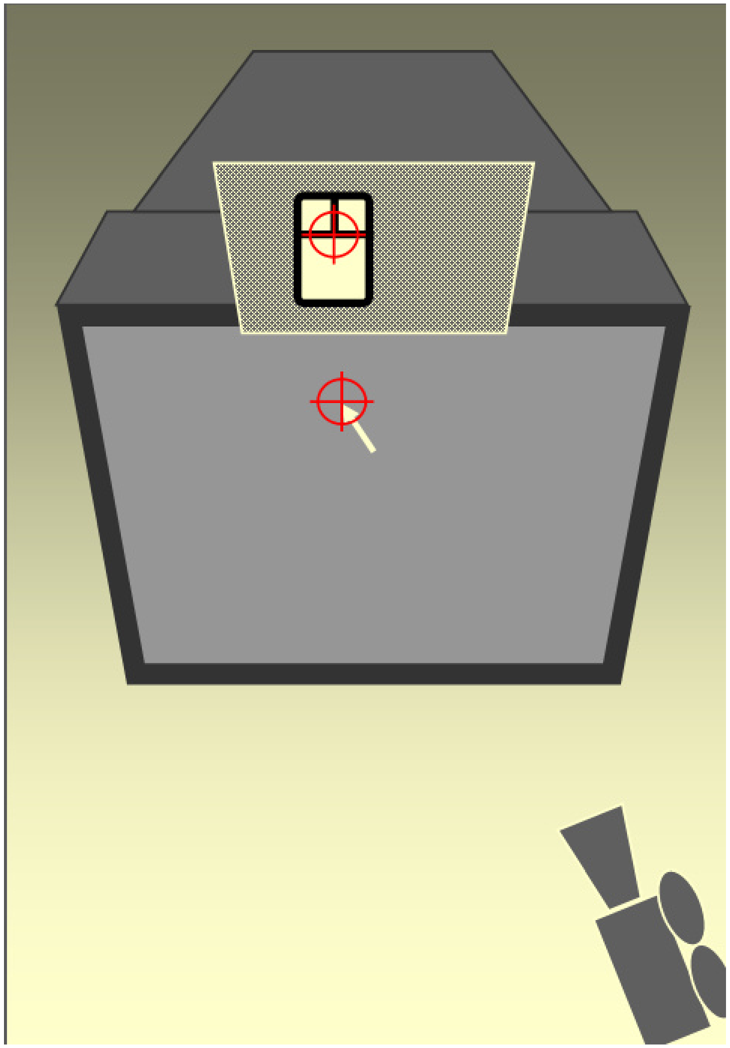
- Use a video camera to capture both input device and response
- Represent motions as two sine waves
- Find difference in phase to determine latency
- Used by Teather *et al.* (2009)
  - 35 ms for early gen. optical mouse on a CRT display
  - +40 ms for optical USB camera tracker

Setup by Teather et al. (camera not shown)



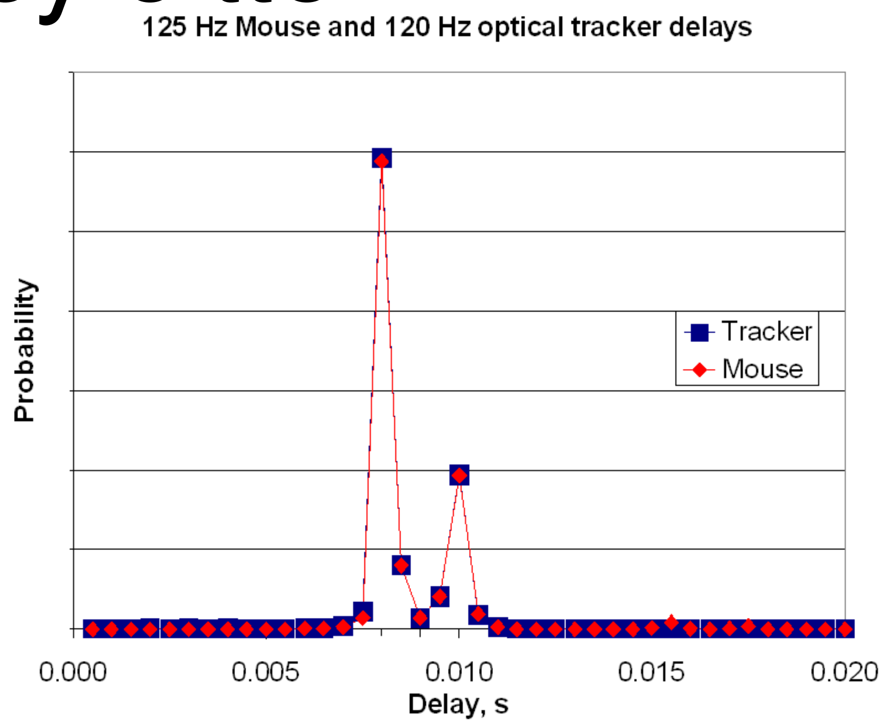
Measuring Latency

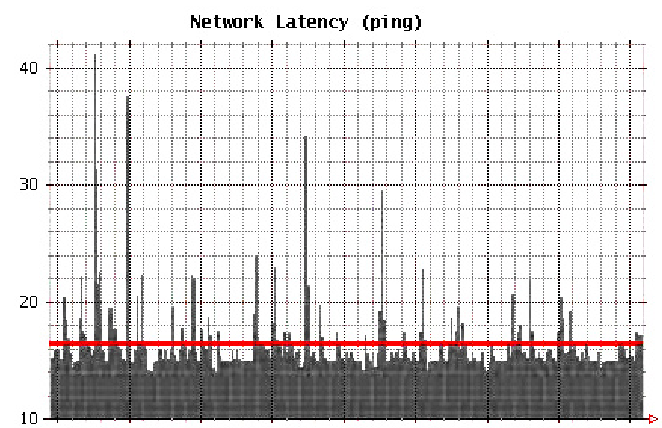
USB mouse (early system)	33.2 ± 2.8 ms
PS/2 mouse	53.1 ± 3.3 ms
USB mouse, 60 Hz LCD	43.2 ± 2.7 ms
Laser pointer, DLP projector, 120 Hz tracking	102.9 ± 2.2 ms
PS/2 wireless mouse, DLP	102.9 ± 3.3 ms
*Wii*mote, DLP	106.3 ± 6.2 ms



Measuring Latency Jitter

- Variations of latency low for co-located systems
  - modern optical mouse: < 10 ms
- Observe update intervals
- Results of study by [Teather *et al.* 2009]
  - 99.5% of mouse updates: 8–11 ms of previous sample
  - Jitter likely dominated by time jitter of OS scheduler
- Similar results for optical tracker output
  - latency magnitude higher
  - variability alike
- Different for networks!





Latency Jitter Parameters

- Can be described with **RMS** values
- Sometimes better to use long-tailed distributions (esp. network jitter)
  - Large variations = dropouts

Characterizing Dropouts

- Many causes => describing is challenging
- Frequency + duration
  - often Poisson Process
  - simple to implement and to use

Measuring Spatial Jitter

- Immobilize tracking device
- Observe reported positions
  - some devices report static positions
  - others' reported positions fluctuate

- Very low jitter in computer mice
  - Tremor dampened
  - Sensor filtering

Jitter in some devices

- Optitrack optical 3D tracking device, 1 m away from cameras: 0.4 mm mean-to-peak [Teather *et al.* 2009]
- Laser pointer, held with extended arm: 0.20–0.25 degrees mean-to-peak
- Same, held with both hands: 0.10–0.15 degrees mean-to-peak

- 6–8 pixels – assuming a user 2 m away from a 1.5 m wide screen, with horizontal resolution of 1024 pixels

Human Behaviour

Measuring Human Behaviour

- Speed of selection or dragging tasks
- Accuracy
- Ease and comfort
- These are not completely independent
  - ease and comfort can affect both speed and accuracy [Soukoreff, 2004]
  - speed and accuracy have opposing influences onto each other
    - speed-accuracy trade-off
- Common practice: measure and report several dependent measures [MacKenzie, 2001]

Fitts' Law

- Model for serial fast, aimed movements

  $MT = a + b \cdot \log_2 (A/W + 1)$

  MT – movement time

  A – amplitude of movement (distance between targets)

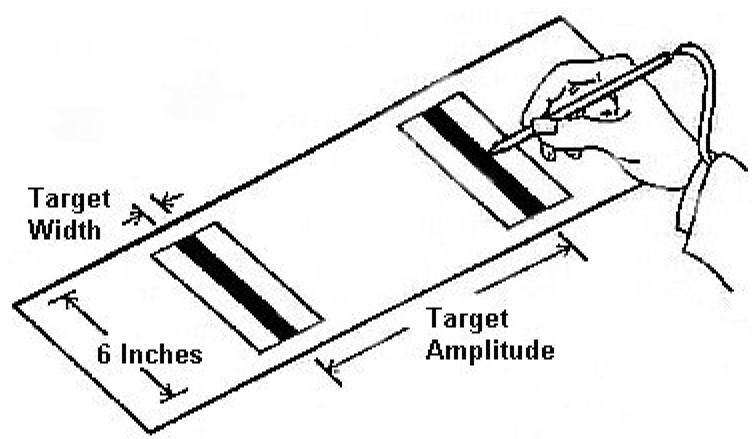
  W – width of a target

- Using "Index of Difficulty"

  $MT = a + b \cdot ID$

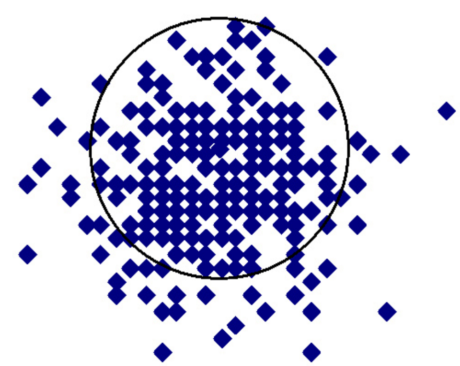
  Index of Difficulty (ID)

- Throughput: $TP = ID / MT$



Effective Width

- Larger targets are hit with fewer misses & relatively closer to their centres
- Smaller targets are missed more often & clicks occur farther away from centres



Effective Width

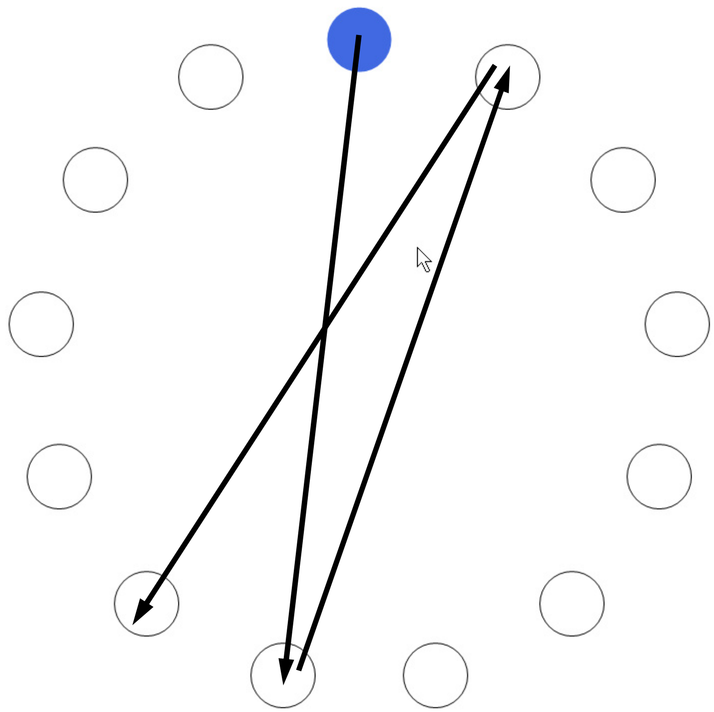
- Observation: points are distributed normally
  - [Crossman, 1957]: use sub-range of hit data as *effective width*
  - 96 % of hits
  - ~4.133 standard deviations of observed hit coordinates:

$$W_e = 4.133 \cdot \sigma$$

- Benefits
  - Better correlations of Fitts' Law with experimental data
  - Especially for small Ids
- Others used it later [MacKenzie, 1992; Douglas *et al*., 1999; MacKenzie & Jusoh, 2001; Myers et al., 2002; Oh & Stuerzlinger, 2002]

ISO 9241-9

- Used for pointing device evaluation
- Multiple targets in a circle

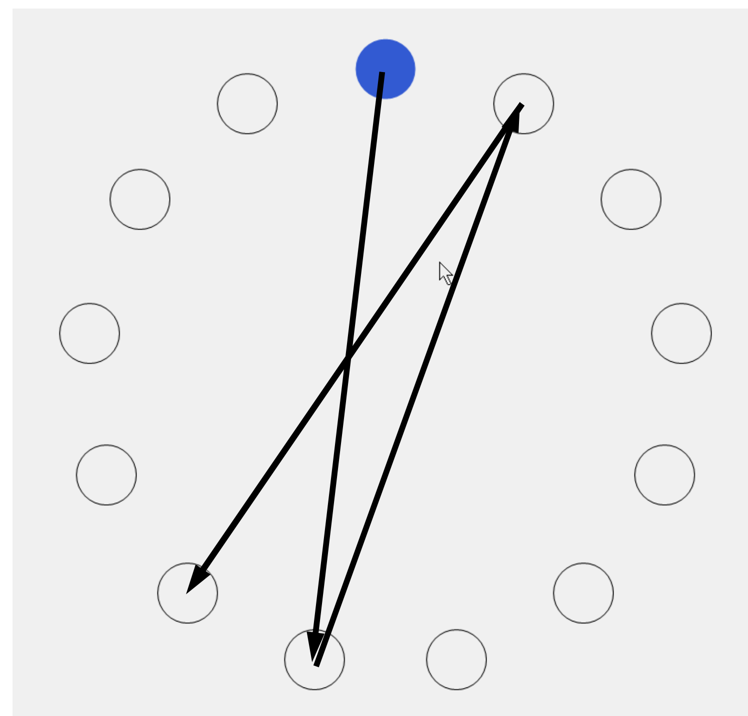


Controlling for Confounding Factors

- Environmental factors
  - lighting variations
  - outside temperature
  - time of day…
- Also, system should have the lowest practically achievable latency and jitter
  - Topic has received more attention in the area of 3D virtual reality, than in HCI

Experiment 1: Latency vs. Spatial Jitter

- ISO 9241-9 procedure
- Desktop PC, 21″ display
- Software added spatial jitter and latency
  - 0, 4, 8, 12, 16 pixels
  - 33, 58, 83, 108, 133 ms
  - 3 widths
  - 2 amplitudes

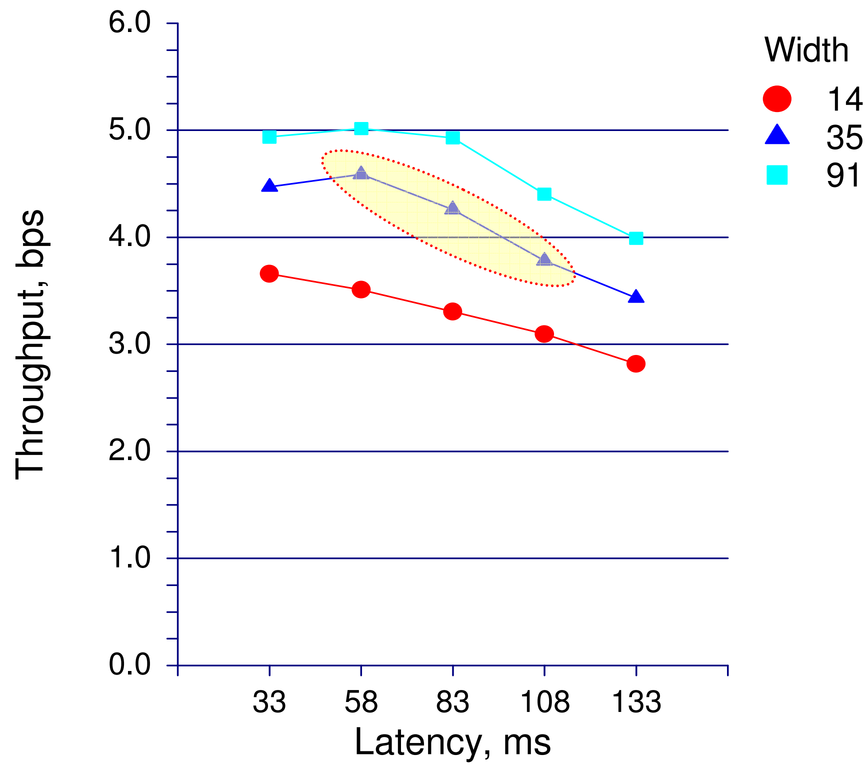


Results – Throughput vs. Latency

- latency: $F_{4,44} = 96.77$, $p < .0001$
- latency × width: $F_{8,88} = 4.97$, $p < .0001$

- Depends on width
- No drop initially
- Afterwards:

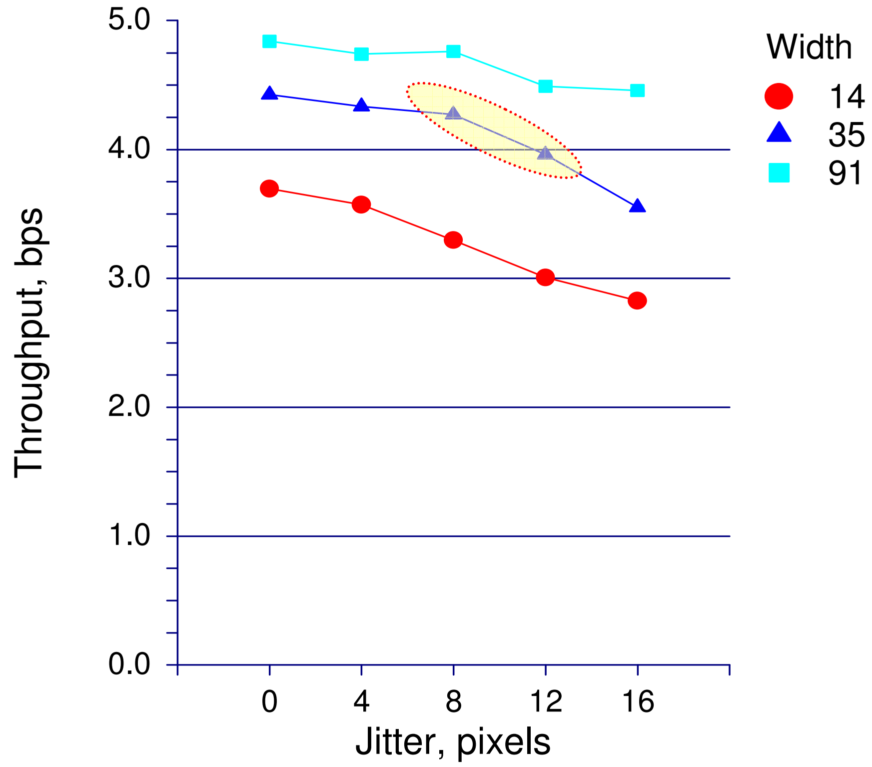
  –0.8 bps per 50 ms



Results – Throughput vs. Jitter

- jitter: $F_{4,44} = 82.83$, $p < .0001$
- jitter × width: $F_{8,88} = 8.20$, $p < .0001$

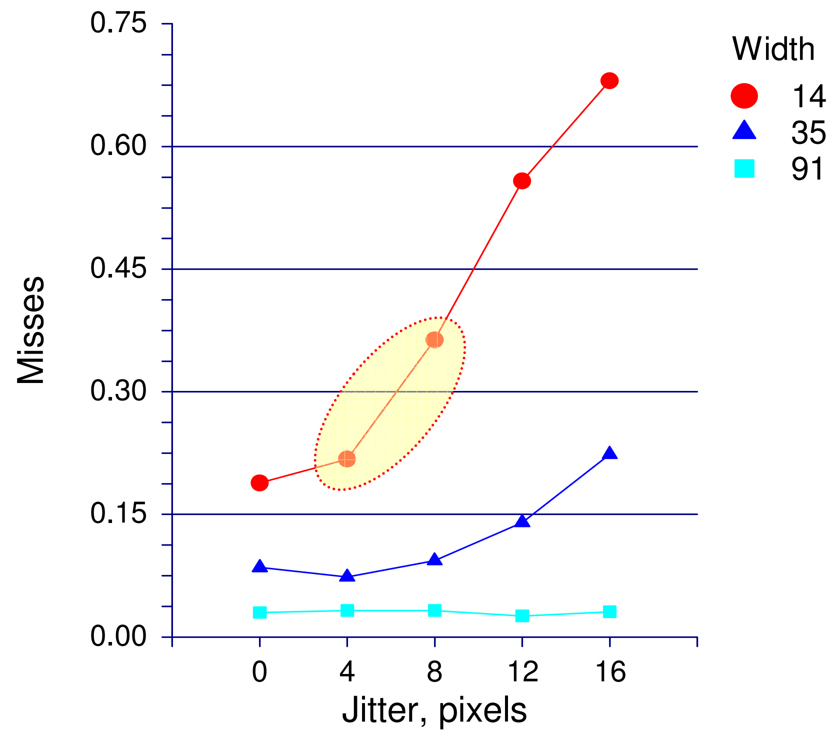
- Depends on width
- No drop initially
- Afterwards:
  - –0.4 bps per 4 pix



Results – Errors vs. Jitter

- jitter: $F_{4,44} = 239.38$, $p < .0001$
- jitter × width: $F_{8,88} = 99.95$, $p < .0001$

- Smaller targets:
  - *dramatic* increase of error rate with increased jitter
  - ~100% per +4 pixels of jitter



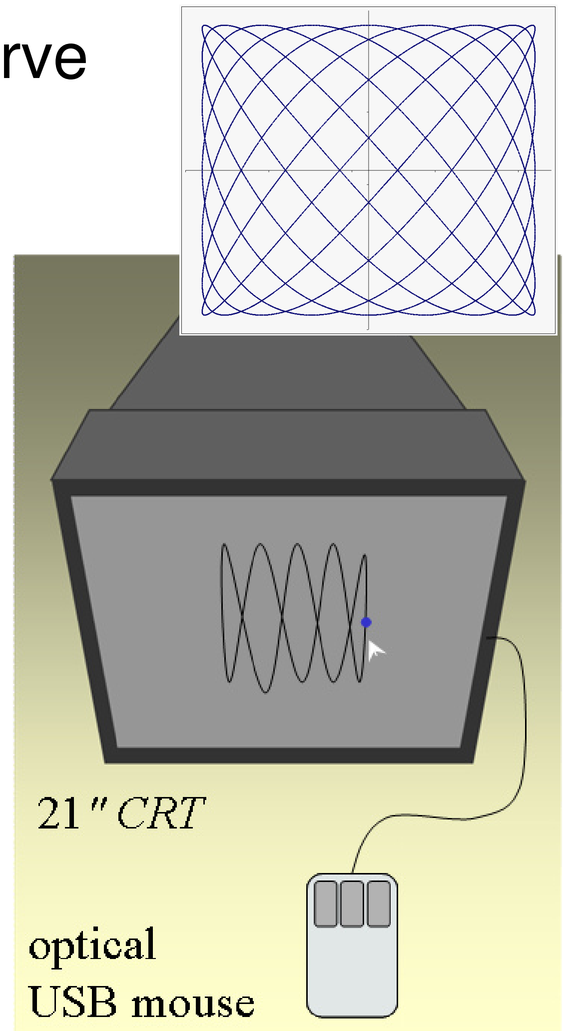
Experiment 2: Pursuit Tracking

- Target motion follows a Lissajous Curve

  $x = A \cdot \sin(a \cdot t + \varphi)$

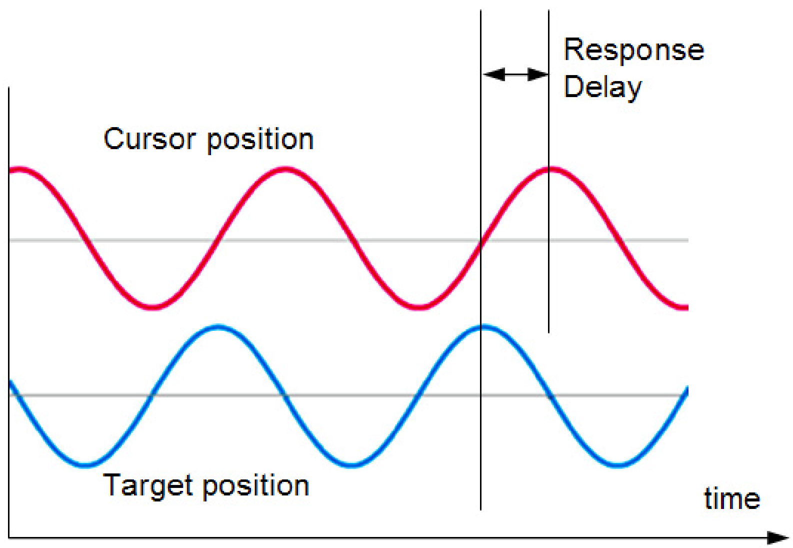
  $y = B \cdot \sin(b \cdot t)$
- Followed with a mouse cursor
  - No clicking!

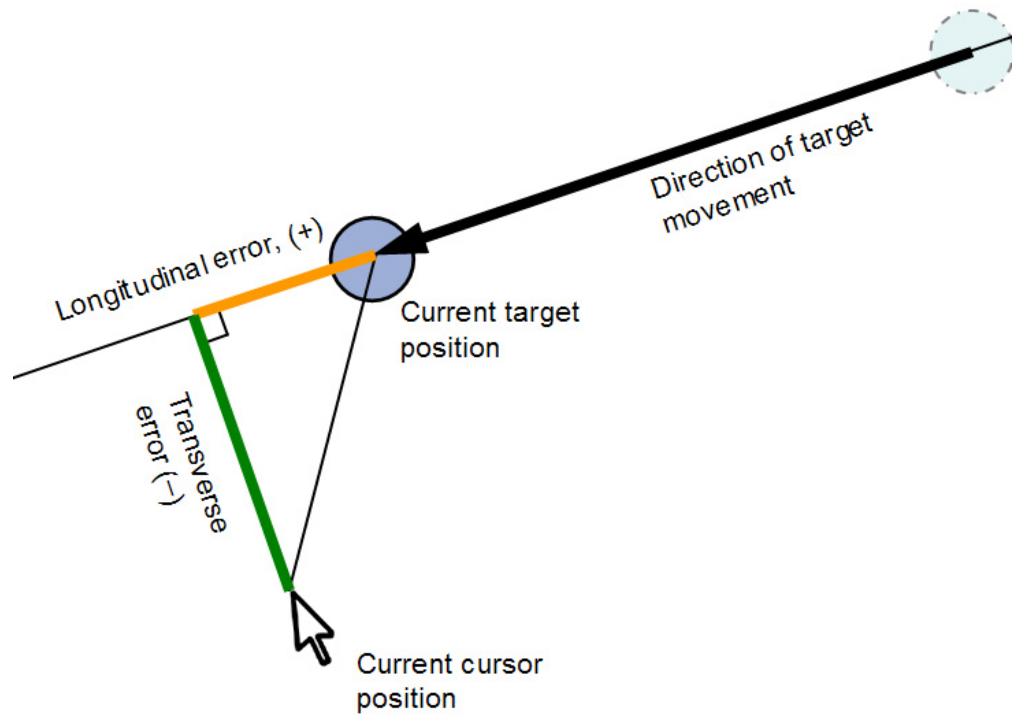
- Latencies: 20–170 ms
- Latency Jitter: 0–60 ms
- Dropouts
  - Up to 20 % mouse events dropped
  - Up to 160 ms in duration
- Speed 8–32 cycles per minute



Dependent Variables

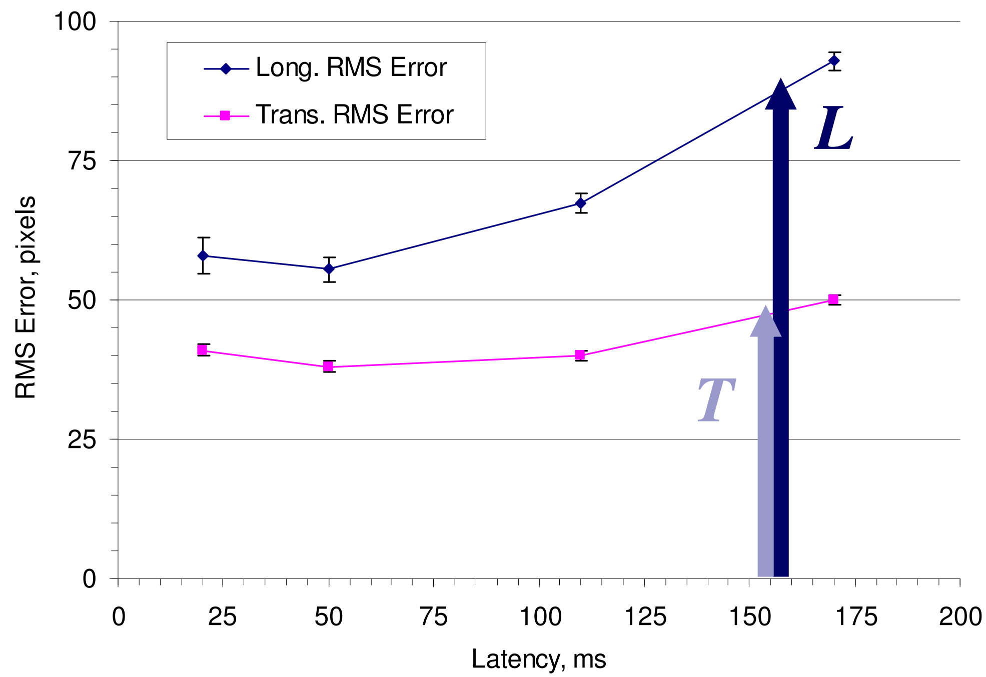
- Errors: Transverse and Longitudinal
- Response delay





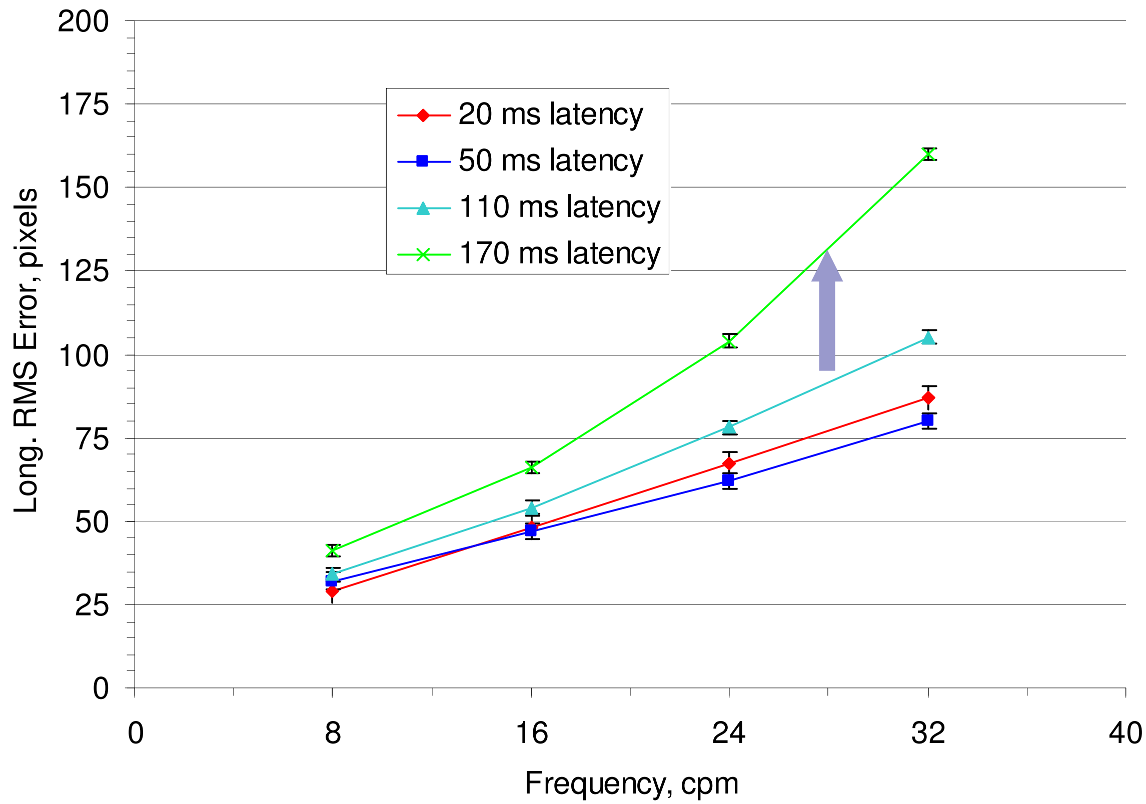
Results – Errors vs. Latency

- Significant main effect (S*ME*) of
  - *Latency* on *Longitudinal (L.) Errors*
  - …on *Transverse (T.) Errors* *(only 170 ms different)*
  - *T < L*



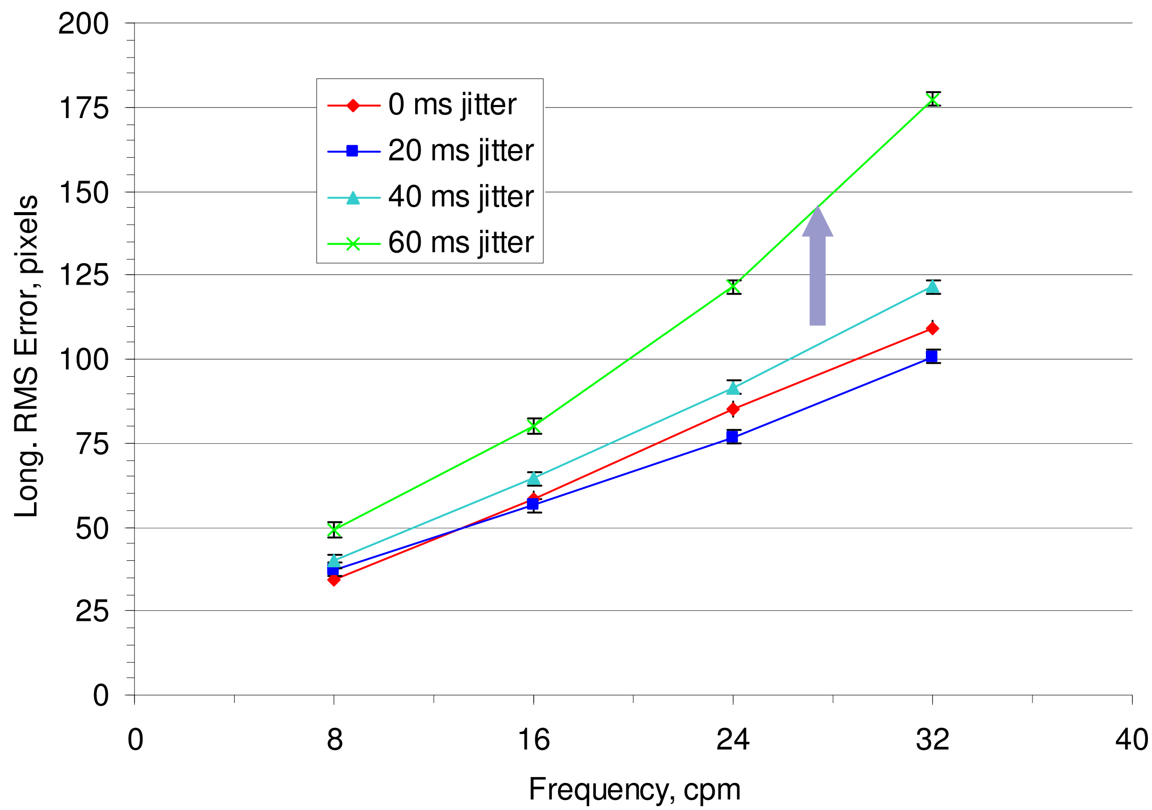
Errors vs. Latency & Speed

- Stronger effect when targets move quickly
- Large jump: 110-170 ms



Errors vs. Latency Jitter & Speed

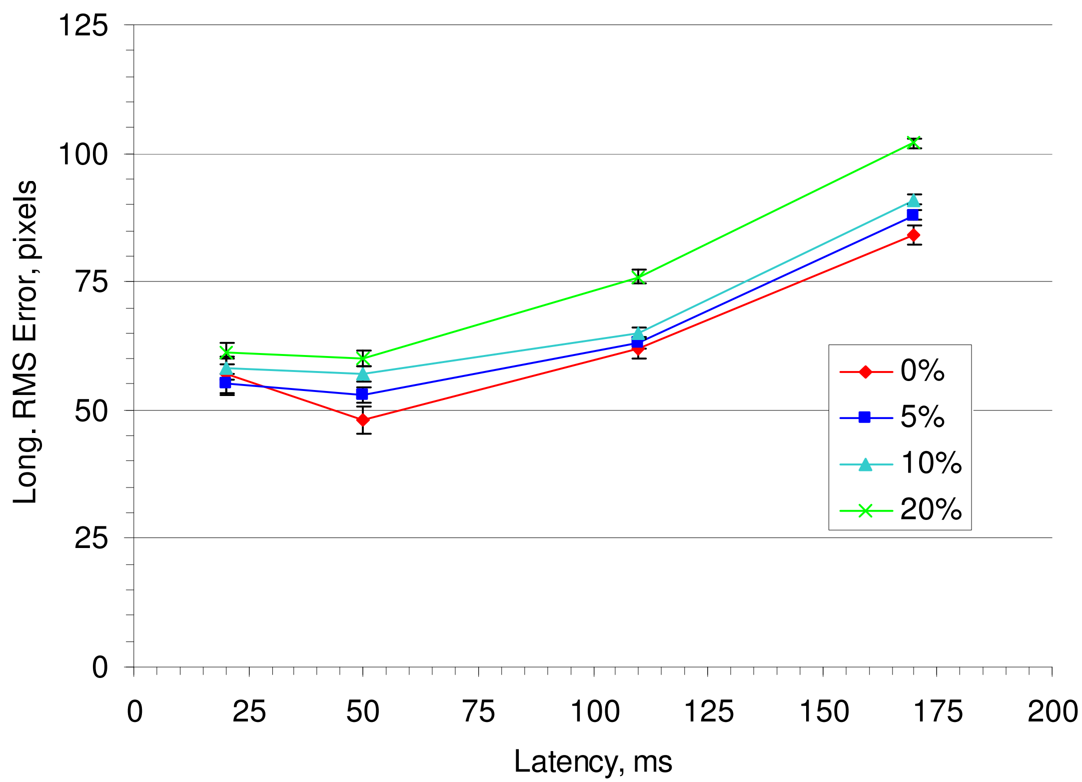
- Stronger effect when targets move quickly
- Large jump: 40→60 ms jitter



*graph for 170 ms

Errors vs. Dropout % & Latency

- Stronger effect at higher latency
- Bad when 20 % of samples dropped



Compensating for Latency, Jitter, and Dropouts

- All described factors have negative impacts
- Can compensation help?

Approaches to Compensate for Lag

- Prediction: area of virtual reality
  - [Jung, Adelstein, & Ellis, 2000; Jung, Adelstein, Bernard & Ellis, 2000] for up to 100 ms look-ahead
    - Participants were able to determine presence of prediction
  - [Wu & Ouhyoung, 2000]: good performance of prediction algorithms in a 3D virtual reality
    - up to 120 % better target following accuracy when compensating for tracker latency of about 130 ms
- Not much work done for 2D pointing
- No work on substantially larger prediction intervals
- What is a practical upper limit on prediction interval?
  - pointing movements are <1000 ms

“Hiding” Latency

- Used in remotely controlled interfaces
- Hide real (delayed) cursor and use a *local* cursor

- Works well for systems with low interactivity
- Inconsistencies between different viewers, if views of application state differ substantially between two users
  - “dead person’s shooting” phenomenon

Approaches to Cope with Spatial Jitter

- Filtering [Bui, 2010, Ch. 5]
  - May introduce lag
- Optical stabilization
  - Increases cost
- Using more than one technology
  - Increases complexity and cost

Trading Jitter for Lag

- Both lag and spatial jitter affect performance
- May have to choose between low jitter or low latency
- How much filtering to apply against jitter?
  - Removing jitter via software filtering increases latency
  - Smoothing can afford better accuracy

- Need to consider existing error rate and cost of correcting errors

Trading Jitter for Lag (2)

- Based on our study,
  - decrease of jitter for small or medium targets 12 → 4 pixels ≡ change in latency of 50 ms
  - (i.e., we're ☺ if we introduce < 50 ms of latency)
- Averaging filter
  - assume noise is random (uncorrelated)
  - reducing jitter by a factor of 3 requires averaging of $3^2 = 9$ samples

Change in latency due to filtering

- Sampling rate = 125 Hz (e.g., USB mouse)
  - 9 samples averaged

    1/125 · 9 = 72 ms of additional delay! ☹

- ☺ Gain more accuracy
  - desirable for small target sizes
  - may not be needed for large targets
    - harmful for some games

Device's Design Improvements

- Using components of better grade
- Improving algorithms
- Hybrid approaches to deal with specific weaknesses

- All comes at cost
  - Price, size, development time…

Summary

- Detrimental effects of system latency, latency jitter, spatial jitter, and dropouts on pointing input, described their origin and fundamental reasons behind their existence
- Methods for measuring these factors in a system
- Methods for measuring human performance
- Ways of dealing with negative factors
  - prediction, filtering, optical stabilization, and system redesign directions