3D User Interfaces for Games and Virtual Reality

Lecture #5: Human Factors

Spring 2020

Joseph J. LaViola Jr.

Overview

Goal

- Provide an overview of key human factors in areas perception, cognition and physical ergonomics
- State how issues can be analysed through specific validation methods

Introduction

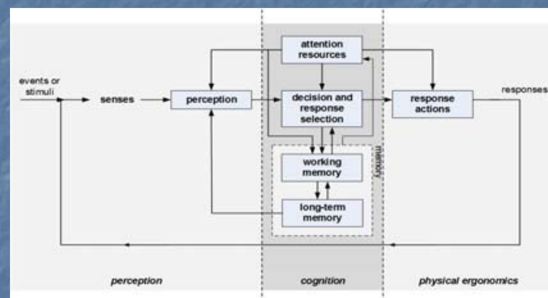
- “Human factors” refers to capabilities characteristics, and limitations of the human user, and includes:
  - Considerations related to the body (acting)
  - Senses (perceiving)
  - Brain (thinking)

Introduction

- What is human-factors driven design?
  - Close analysis of human factors to design 3D user interface techniques and devices
  - Depends on use case and users, integral part of UCD
  - Analyse true limitations but also capabilities of human body, strongly tied to validations

Information Processing

Mechanisms underlying human factors are often grounded in human information processing



Information processing and related human factors issues. Adapted from (Wickens and Carswell 1997)

Attention

- Attention resources and processes affect information processing at various stages
  - Three components: orienting to sensory events, detecting signals for focused processing, maintaining a vigilant or alert state
  - Attention can be selective, focused or divided
  - Prone to errors
  - Major component in processing visual stimuli and search behavior

Decision-Making

- Decision-making is key to information processing
  - Depends on capturing, organizing, and combining information from various sources
  - Process of choosing between two or more alternatives, resulting in real or imaginary consequences
  - Speed of decision-making processes varies widely
  - Can be modelled, for example in decision trees

Behavior

- Behavior refers to the usage of specific strategies to make decisions
  - May be formed through experience
  - Can be affected by culture, belief, habits, social norms, or attitudes, and emotion
  - Can also be affected by *conditioning* and *habituation*
- Behavior can be modelled, and often informs the design of *natural user interfaces* (Wigdor and Dixon, 2011)

Skills

- User behavior is often affected by skills
  - Skills allow users to make more accurate and quicker responses and can be acquired over time by repeatedly performing similar actions
  - Ties into decision-making, memory and motor processes
  - Skills are thought to be stored as nondeclarative knowledge in our long-term memory
  - Skill acquisition through declarative, associative and autonomous stages

Selection and Control of Action

- Involves the selection and performance of a response based on certain stimuli
- Speed and accuracy of responses are dependent on various factors
  - Accuracy (speed-accuracy trade-off), stimulus-response compatibility, similarity, task switching, uncertainty and precuing
- (Motor) control is either open-loop or closed-loop

Movement: Fitts's law

- Fitts's law affects control performance
  - Key in describing the performance of many motor actions, often used in validations
  - It describes the time to make aimed movements to a target location (Fitts 1954)

$$MT = a + b \log_2 (2D/W)$$

- MT is movement time, a and b are constants (model parameters), D is the distance to the target, and W is the target size
- Performance time increases both by increasing the *distance* towards a target and decreasing the *target width*

Movement: Index of Difficulty

- Movements can be divided into two phases
  - a fast motion towards the target (also known as the ballistic phase)
  - a corrective movement, used to home in on the target once it's nearby
- Latter relates directly to the *index of difficulty (ID)*, the quantity of information transmitted (in units of bits) by performing the task, which can be defined by

$$ID = \log_2 (2D/W)$$

- D is the distance to the target, and W is the target size

Movement: Index of Performance

- Fitts's law and ID metrics can be combined to form the *index of performance (IP),* defined as

  IP = (ID/MT)

- IP is expressed in bits per second and has been used to define the performance of many input devices
  - in one study, the hand itself was found to have 10.6 bits/s, a mouse 10.4 bits/s, a joystick 5.0 bits/s, and a touchpad 1.6 bits/s (MacKenzie 1992)

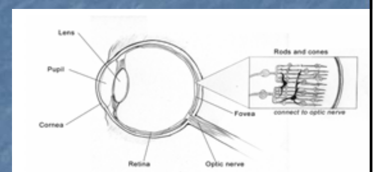
Movement: Steering Law

- Steering law is a predictive model that describes the time to steer (move or navigate) through a tunnel
  - Tunnel can be understood as a path with a certain width
  - The model is associated with the task of moving through the tunnel as quickly as possible without crossing the boundaries
- For simple paths (i.e., straight tunnels with a constant width *W*), the steering law can be represented by the following formula, where *A* is simply the length of the path

$$T = a + b\frac{A}{W}$$

Vision

- Photoreceptors and nerve cells convert light into electrical signals and transmit them to the brain's primary visual cortex via the optic nerves
  - The distribution of photoreceptors (rods and cones) results in different abilities of the visual system in the center and the periphery
- Processing of visual information depends on a complex pattern of intertwined pathways
  - Dorsal / ventral pathway important for processing information (bottom up or top down)



The human eye.
(Image courtesy of Ernst Kruijff)

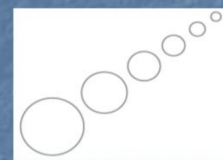
Visual Cues

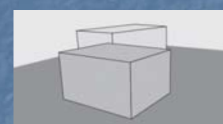
- Depth cues aid users to interpret a visual scene correctly for effective use
- Achieved through visual cues in the displayed content
- However, cues may conflict

Visual Cues

Following visual cues convey important depth information

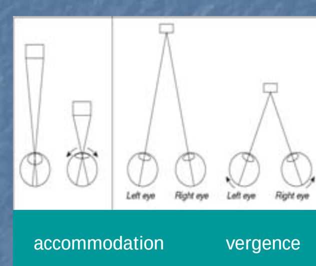
- Monocular, static cues
  - Relative size, height relative to horizon
  - Occlusion
  - Linear perspective
  - Aerial perspective (atmospheric attenuation)
  - Shadows and lighting
  - Texture gradient



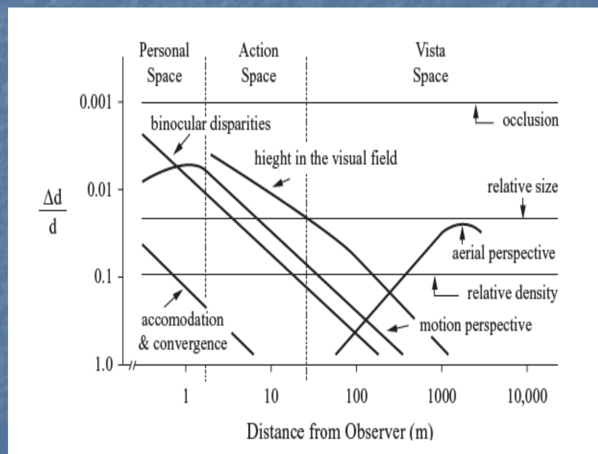


Visual Cues

- Oculomotor cues
  - Vergence and accommodation
- Motion parallax
- Binocular disparity and stereopsis



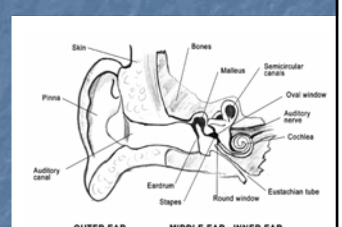
Visual Cues: Relative Importance



Relative importance of depth cues at different distances, adapted from Cutting et al. (1995)

Audition

- Ear can process frequencies between approximately 20 and 20,000 Hz, detects loudness, pitch, and timbre
  - Infrasonic / ultrasonic sounds may not be detected, can have other effects
  - Humans are good at localizing sound sources through the intensity difference between the ears, especially when sound comes from the frontal hemisphere
  - Sound is rapidly detected and can have an alerting functionality
  - Ability to focus on specific sounds, filtering out others



The human ear.
(Image courtesy of Ernst Kruijff)

Auditory Cues

- **Binaural cues** arise from a comparison of the sound waves received by each ear
  - Interaural time difference (ITD): the difference in time between the arrival of the sound to each ear
    - Sound source's lateral location
  - Interaural intensity difference (IID) : the difference in sound intensities arriving at each ear
  - Some ambiguous sound locations around head

Auditory Cues

- **Head-related transfer functions** (HRTFs) are the spatial filters that describe how sound waves interact with the listener's torso, shoulders, head, and outer ears
  - Modify sound waves from a sound source in a location-dependent manner to provide a localization cue
  - Can contain much of the spatial information
  - Can help with the ambiguous cases
  - Have limitations and are often listener specific, though generalized solutions are (becoming) available

Auditory Cues

- **Reverberation** is the collection of reflected waves from various surfaces within a space
  - Acts as an important acoustical cue for localizing sound sources
  - Aids in the perception of source distance
  - Provides information about the size and configuration of a listening environment, including geometry and surface properties

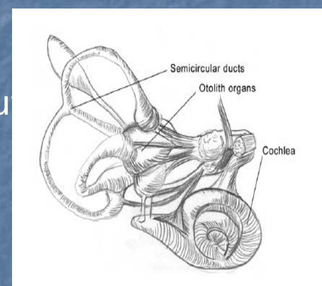
Auditory Cues

- **Sound intensity** (loudness) is a primary cue for determining a sound source's distance, because intensity will decrease as the distance to the source increases

Auditory Cues

Vestibular Cues

- Human balance system
  - Vestibular system not strictly part of the auditory system, but uses the same nerve
  - Consists of otolith organs (linear movement) and three semicircular ducts (rotational movement)
  - Has affect on cybersickness: minimal cues can help



The vestibular system. (Image courtesy of Ernst Kruijff)

Somatosensory

- Handles **haptic** sensations
  - Perceives cutaneous (skin) and subcutaneous (below skin) sensations, the position of the body and limbs (proprioception), and mechanical sensations in the joints and muscles
  - Provide the human with information such as geometry, roughness (touch), and weight and inertia (force)

Somatosensory Cues

Tactile Cues

- Perceived by a variety of cutaneous mechanoreceptors that produce information about surface texture and pressure
  - Mainly achieved by skin depression and deformation
  - Brief events, prolonged events without displacement, prolonged events with displacement
  - Variety of events allows us to sense a variety of object properties, including rigidity or plasticity, friction, texture, and resistance

Somatosensory Cues

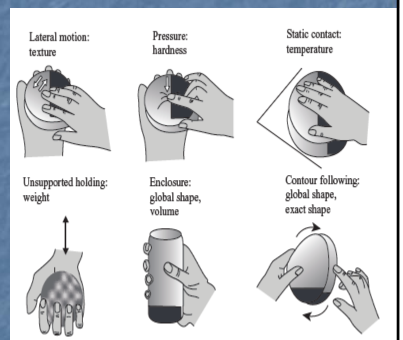
Thermal Cues and Pain

- Thermoreceptor senses relative changes in temperature through both warm and cold receptors
  - Sometimes cold receptors also may respond to higher temperature, which may result in paradoxical responses to heat
- Nociceptors (pain) also respond to stimuli that may potentially damage the body

Somatosensory Cues

Kinesthetic and Proprioceptive Cues

- Help to determine the relationship between the body and physical objects through muscular tension
  - Can be both active and passive
- Proprioceptive cues provide people with information about the position and angle of body joints
- Both tactile and kinesthetic cues are important in haptic perception

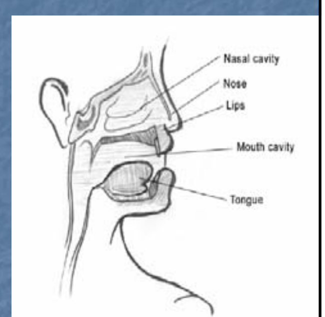


Exploratory procedures for understanding object properties. Redrawn from Lederman and Klatzky (1987)

Spring 2020 CAP6121 – 3D User Interfaces for Games and Virtual Reality ©Joseph J. LaViola Jr.

Chemical

- Human chemical system handles both smell (olfaction) and taste (gustation) sensations
  - Both systems are functionally linked
  - Gatekeepers to the human body
  - Direct connection to brain



The chemical system. (Image courtesy of Ernst Kruijff)

Spring 2020 CAP6121 – 3D User Interfaces for Games and Virtual Reality ©Joseph J. LaViola Jr.

Chemical Cues

Olfactory Cues

- Olfactory stimuli mainly provide us with a range of odor cues
  - No successful or generally accepted categorization exists
  - We are able to separate and group cues through perceptual organization
  - Smell is especially well suited for danger detection
  - How many scents humans detect varies widely, and complex scents are easier to remember
  - Olfactory cues have been shown to trigger emotional events or memories

Chemical Cues

Gustatory Cues

- Just as with smells, there is no standard classification of tastes
  - Five basic tastes—sweet, sour, salty, bitter, and umami (savory or meaty flavor, coming from a Japanese categorization)—seem to be generally accepted
  - Our taste system is able to sense several more sensations, such as coolness, numbness, fattiness, and spiciness (or pungency)

Chemical Cues

Flavor

- Flavor sensations are triggered by combined olfactory and gustatory cues
  - What most people often describe as taste is actually flavor
  - Flavor sensations are easily combined, as the mouth and nasal cavities are not only functionally and physically linked
  - Flavor can be influenced by a person's expectations and satiety

Sensory Substitution

- When designing a 3D UI, it often happens that a specific sensory channel cannot be used
  - Blocked on the user or the technical side
  - Interface designers often try to "translate" the missing information over another sensory channel, a process called sensory substitution
  - Can occur between and within sensory channels
  - Makes use of the *plasticity of the brain*
  - Requires caution as the information-processing loop is reordered

Multisensory Processing

- Add or integrate sensory channels
  - Sensory channels are no longer seen as separate channels, because they may affect each other: multisensory processing of this sort occurs more often than is regularly believed
    - Multisensory processing theory builds upon the integration of sensory signals in so-called multimodal association areas within the brain
    - Affected by *cross-modal effects*, including bias, transfer enrichment

Evaluating Perceptual Issues

- Providing a complete overview of all perceptual problems that may occur in 3D UIs is virtually impossible, as the issues span numerous dimensions
- A general discussion of human factors limitations related to perception can be found in Stanney et al. (1998)

Evaluating Perceptual Issues

Typical Visual Issues

- In VR, often caused by limited display fidelity
  - Includes the provision of adequate motion cues, lack of appropriate stereopsis cues, inadequate visualization of one's own body, depth underestimation and overestimation
- In AR, caused by various stages in "pipeline" encompassing among others the environment, the display device or the user
  - Includes depth ordering, visibility and legibility issues, object segmentations, scene abstraction problems

Evaluating Perceptual Issues

Typical Non-Visual Issues

- Problems are often related to the limitations in reproducing realistic cues
  - *Audition*: limits in localizing a cue or drawing the user's attention
  - *Somatosensory*: low accuracy feedback
  - *Chemical*: reproduction of exact smell or taste

Evaluating Perceptual Issues

Subjective Methods

- User-preference scales can provide insights not only into the overall preference of the user but also into the quality of specific cues
  - Much of this is in line with normal user study methodology
- Some perceptual constructs can be assessed using specific methods, including:
  - Cybersickness, for example using SSQ
  - Presence, for example using IPQ

Evaluating Perceptual Issues

Performance Measures

- Some performance measures relate to information processing and are used to analyze information quality and accuracy
- Perceptual issues are also of interest in the analysis of motor action performance (mostly Fitts's law)
- Various efforts to isolate the specific effects of certain perceptual stimuli, in particular in the area of visual perception

Evaluating Perceptual Issues

Psycho-Physiological Methods

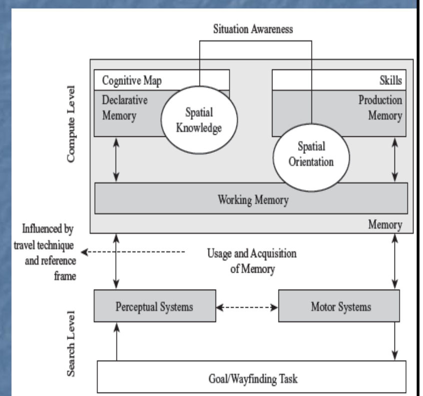
- Used to address perceptual issues, in particular for visual perception
- Predominant method is eye tracking
  - Process of measuring the point of gaze of a user
  - Eye tracking hardware and software allows the analysis of different kinds of eye movements, including eye fixations and saccades
  - Analysis can reveal areas of interest and the number of visits to specific areas (visualized using heat maps)
  - May require careful calibration and may not always be accurate in dynamic environments

Cognition

- Often associated with “knowledge stored in the brain”
  - Cognition governs processes in memory, language, and thought, but is also directly linked to our perception and attention
  - Knowledge depends on *representations*
  - Both short term (temporal, different memory spans between people) and long-term memory, with different functions
  - *Recalling information* from long-term memory requires specific memory traces to be reactivated through pattern completion and recapitulation

Situation Awareness

- Situation awareness is generally characterized as the internalized model of the current state of the user's environment
  - Affects how we interact with the objects around us
  - Links to wayfinding



a representation of wayfinding as a decision-making process

Cognitive Mapping

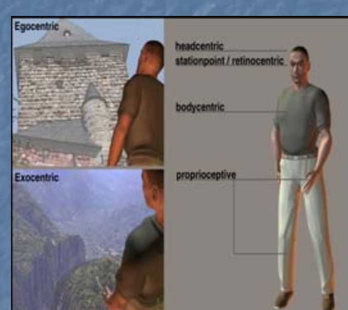
- The process of accessing, using, and building the treelike structures in the cognitive map is also called *cognitive mapping*
  - Environmental information is stored in our long-term memory and is generally referred to as the *cognitive map*
  - During a wayfinding task, we make use of existing spatial knowledge, acquire new spatial knowledge, or use a combination of both
  - Knowledge of our location and viewing direction is called *spatial orientation*, while the combination of spatial orientation and spatial knowledge (cognitive map) contributes to what we previously labeled *situation awareness*

Types of Spatial Knowledge

- During wayfinding, people obtain different kinds of spatial knowledge
  - Landmark knowledge
  - Procedural knowledge (or route knowledge)
  - Survey knowledge
- Search strategies and movement parameters influence the effectiveness of spatial knowledge acquisition

Reference Frames and Spatial Judgments

- During real-life motion, we feel as if we are in the center of space, a phenomenon that is called *egomotion*
- Egocentric reference frame is defined relative to a certain part of the human body
  - Provides distance and orientation cues
- Exocentric reference frame is object- or world-relative



Human reference frames (right) and associated views (left). In an egocentric view (top left), the user is inside the environment, while in exocentric view (bottom left), the user is outside the environment, looking in (Image courtesy of Ernst Kruijff).

Typical Issues

- *Mental load*, also referred to as cognitive load, refers to the amount of cognitive work or effort required by a task or situation
  - Affected by exogenous and endogenous demands
  - Germane processes mas also have an effect
  - User abilities and skills contribute can reduce mental load
  - Different stages in the information-processing pipeline can be used to define the various dimensions in which resource allocation takes place

Typical Issues

- *Human error* refers to a lack of success in task performance
  - Can be defined as failing to meet an arbitrary implicit or explicit criterion
  - Can also occur because of sensory or motor limitations
  - Ties into the complete cycle of human information processing
  - Bias, misattribution, and suggestion can be major error sources
  - Similar to mental load, human error is strongly tied to our abilities and skills and depends on attention mechanisms
  - Human error and mental load are related

Evaluating Cognitive Issues

Subjective Methods

- Most frequently applied category of cognitive load measurements
  - Often help to explain separately measured performance issues
  - Two most popular and frequently interconnected methods are SBSOD and NASA TLX

Evaluating Cognitive Issues

Performance Measures

- Far less often used in domain of user interface validation, yet there are some powerful methods that have been used in other domains
  - *SAGAT* (Situation Awareness Global Assessment Technique) is one example, a query technique developed by Endsley (1988)
  - Assessment of human errors has often been used to address the probability of human failures to perform a risk analysis, represented in tree-like structures (fault and event trees)

Evaluating Cognitive Issues

Psycho-Physiological Methods

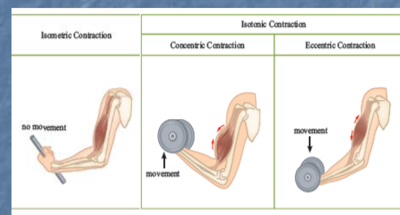
- As mental workload is essentially physiological, various techniques have been used, including:
  - Heart rate, pupil dilation, and eye movements, and brain activity using electroencephalography (EEG)
- Physiological methods have also been used to measure stress and anxiety

Ergonomics

- We primarily focus on physical ergonomics
  - Related primarily to the human musculoskeletal system
  - Depends on the anatomical capacities of the different parts of the human body, which defines how and how well we can perform a specific task

Ergonomics Foundations

- About 600 different muscles in the human body
- Human body affords a wide range of motions
- Muscle contraction is isometric or isotonic

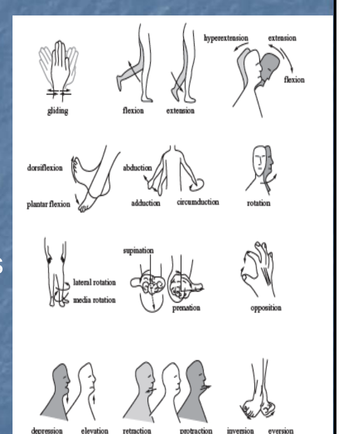


isometric versus isotonic contraction

in a **concentric** contraction, the muscle tension rises to meet the resistance, after which it remains the same as the muscle shorten
in **eccentric** contractions, the muscle lengthens due to the resistance being greater than the force the muscle is producing

Motion Types

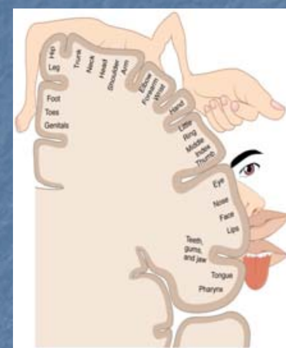
- Human motion is produced by our joints and muscles and is often a response to a stimulus
  - Peripheral nervous system triggers effectors via electric signals, can result in voluntary (motor) and involuntary actions
  - Most human output can be defined as a control task (affected by control-body linkage)
  - Control task can be characterized by its accuracy, speed and frequency, degrees of freedom, direction, and duration



Selected physical motion types.
(Image courtesy of Ernst Kruijff)

Sensory-Motor Distribution

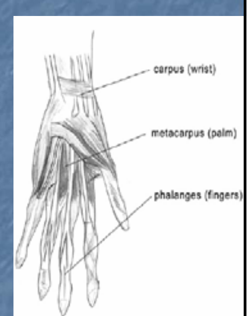
- Sensory-motor distribution of the cortex is of importance for the performance for the different body parts
  - Homunculus represents the mapping of the body parts (in particular the skin) to the cortex
  - Relates to the possible precision with which tasks can be performed



The sensory homunculus.
(wikimedia commons)

Hands and Arms

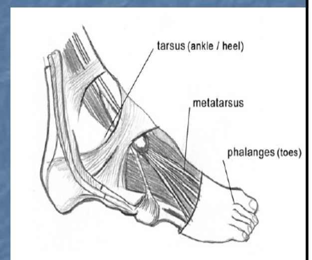
- Hand is the most dominant human control channel
  - Hand, wrist, and arm is a lever system and allows for a large number of control dimensions
  - Affords both coarse and fine motor actions
  - Depending on the hand-device coupling, humans can perform actions using a power grip of or a precision grip: handle and grip design are important!
  - Unimanual and bimanual tasks



The hand.
(Image courtesy of Ernst Kruijff)

Feet and Legs

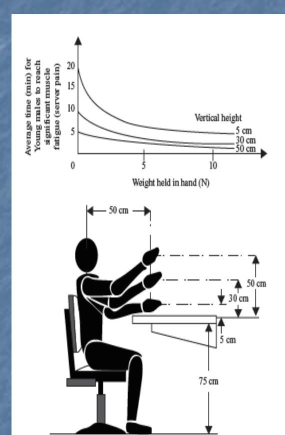
- Feet and legs are also used often during interaction
  - Ankle and toes allows several movements that partly resemble the movements of the hand
  - Leg-ankle is lever system



The Foot.
(Image courtesy of Ernst Kruijff)

Posture

- Posture is an important factor that affects user comfort and fatigue, up to the point of being unable to interact any longer
  - Analysis influenced by workplace design
  - Since most 3D UIs use hand-coupled devices or gestures, the relationships between arms and the rest of the body are critical
- Shoulder and arm fatigue will occur when users need to operate with an uncomfortable or unsupported arm pose for a prolonged time



Expected time to reach shoulder muscle fatigue, redrawn from Chaffin and Anderson (1991).

Typical Issues

- **Fatigue**
  - Humans experience fatigue when load tolerance is surpassed, which depends not just on the user's muscles, bones, and ligaments, but also pain tolerance
    - Often related to the pose
    - May occur in the shoulder and back as well as in the arms and wrists
    - Typical signs of fatigue include change of pose, lowering of arms and hands, or the regrasping of an input device
  - Can also affect mental stress
  - Fatigue can result in errors during task performance, as well as increased performance time

Typical Issues

- **User Comfort**
  - Related to fatigue, user comfort spans both physical and psychological dimensions
  - Comfort refers to a state of ease, which may include the absence of pain
    - Generally refers to taking and maintaining a comfortable pose over potentially prolonged durations or keeping a comfortable grip on a specific device
    - Can include both physical comfort as well as design factors such as surface texture or shape of devices

Evaluating Ergonomics

Subjective Measures

- Assessing user comfort often requires customized questionnaires for your specific system and application
- Measures of user comfort and fatigue will be mixed, as both are interrelated and often difficult for users to separate

Evaluating Ergonomics

Performance Measures

- Difficult to evaluate the relationship between performance and fatigue or user comfort, but some methods can be used
  - Task performance analysis, including error analysis, can be correlated with other methods of fatigue over time
  - Observations may help

Evaluating Ergonomics

Psycho-Physiological Methods

- Physiological methods have been used to assess fatigue
  - Often coupled to specific models that define biomechanical principles
    - Models are mostly specialized for specific tasks, such as lifting or push-and-pull tasks
  - EMG (electromyography, sensing muscle activity) has been applied to address muscle tension and fatigue
  - Some physical devices exist that measure specific muscle and joint groups

Guidelines

- Analyze, design, and evaluate interfaces with human factors in mind
- Refer to the general human factors literature
- Try to isolate human factors issues
- Assess the true potential of the human body to design alternative interfaces
- Consider longitudinal studies

Conclusion

- We introduced key human factors topics
  - Solid foundation of perception, cognition and physical ergonomics for user-centered design processes
  - Important to design effective techniques and devices

Next Class

- Basic Human Computer Interaction
- Readings
  - LaViola – Chapter 3