MLMI10
Designing Intelligent Interactive Systems

Lecture 5

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Lent 2022

Key Concepts

- Embodiment design
- Human capabilities and limitations
  - Sensing and perception
  - Communication
  - Motor control
  - Cognition
  - Control

Report progress so far

- Problem context
- Requirements specification
- Conceptual design
  - Function model(s)
  - Morphological chart
  - Generated conceptual designs
  - Concept evaluation
  - Parameter analysis (or other applicable method)
- Embodiment design
- Risk assessment
- Verification and validation
  - Verification Cross-Reference Matrix (VCRM)
  - Evaluation in context
- Summary

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Embodiment Design

From Concept to Product

1. Conceptual design
   – Determination of the overall function
   – Establishment of function structures
   – Generation and selection of suitable combinations
2. Embodiment design
   – Developing design concepts

- Detailed design
  – Highly application-specific process resulting in a product that can be verified, validated and manufactured

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System design for intelligent interactive systems

- Embodiment design means taking a conceptual design to a prototype-level: identifying algorithms, software libraries, ML approaches, user interface design, workflow, any sensors and additional hardware, etc. and describe how they all interrelate to carry out the overall function
- For example, in the case of a smart wearable device embodiment design would entail:
  - Sketching the device
  - Sketching the user interface design
  - Creating a workflow describing how users are meant to interact with the device
  - Identifying component types (not necessarily specific components to be procured; nor detailed circuit layouts)
  - Identifying ML approaches (what type of ML algorithm, how is data sourced, etc.)
- In classic engineering design methodology, the embodiment design stage is a distinct stage immediately following conceptual design
- **However,** for an intelligent interactive system, conceptual design and embodiment design (and to some extent detailed design) are often entangled
- **The design process is rarely linear although the final design documentation will give this impression**

Example

- SNPS: Devise a wedding ring that allows the bearer to both receive and signal affection
- Overall function: **Provide Affective Coupling**
- Significant sub-functions:
  1. **Display Affection**
  2. **Signal Affection**
- How do we decompose **Display Affection?**
  – May require significant prototyping to identify suitable form factor, electronics solution, materials for pleasant visualisation within the ring
  – In addition, networking component will require pairing with mobile phone or similar device and thus an app on the user's phone

Example

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  1. **Display Affection**
  2. **Signal Affection**
- How do we decompose **Signal Affection?**
  - May require significant prototyping to identify suitable sensor solution, such as capacitive sensing to measure the user stroking the ring and thus modulating the signal (possibly in different interpretable ways; this will then need to be considered when decomposing **Display Affection**)
  - Or might be assumed to be a very simple solution with single hard-key button
  - User testing may be necessary to verify at an early stage that sensor and visualisation solution is deemed attractive for the target audience

Embodiment design

- Selection of components and materials (if applicable)
  - Form factor, power, case
  - Physical buttons, grip, attachment…
  - Determination of parameters such as tolerances, final dimensions, etc.
  - Display, LEDs, sensors
  - You can sketch an embodiment design
    - You are not expected to have arrived at a complete embodiment design that can be sent to the detailed design stage
- User interface
  - Overall design of the most important functions (sketch)
  - Overall workflow for carrying out the most important functions (diagrams)
- Artificial intelligence
  - Description of inference problem: input/output, type of data, particular considerations (e.g. false positives are particularly adverse)
  - Very brief description and motivation of algorithms
  - Data collection

- **Remember that risk, verification and validation is later**

Human Capabilities and Limitations

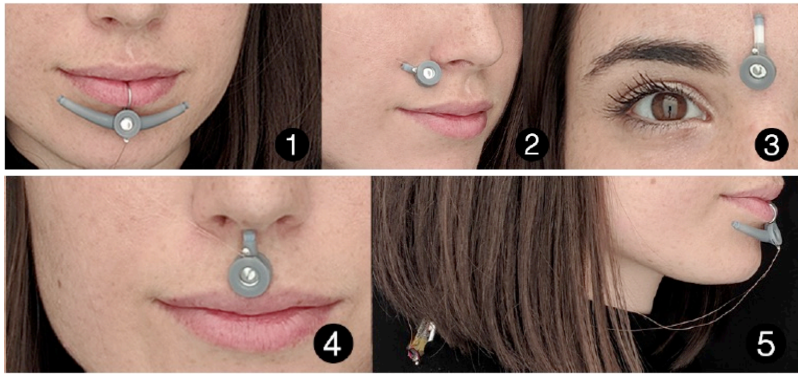
Human capabilities and limitations

- Sensing and perception
- Communication
- Motor control
- Cognition
- Control

Sensing and Perception

Human sensory systems

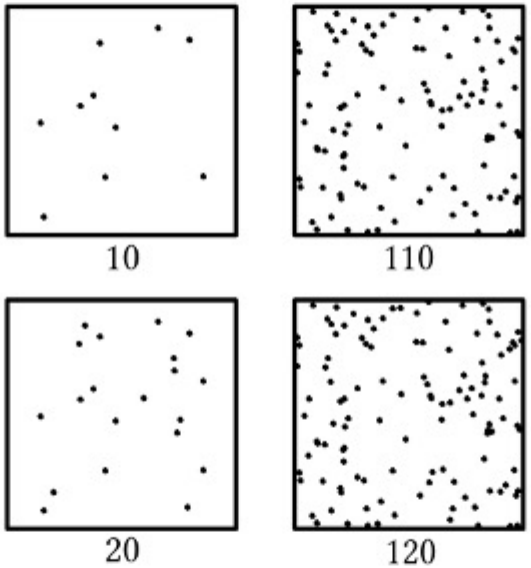
- **External sensation**
  - Visual system → vision
  - Auditory system → hearing
  - Somatosensory system → touch
  - Olfactory system → smell
  - Gustatory system → taste
- **Internal sensation**
  - Vestibular system → balance
  - Proprioception → body position
  - Nociception → pain
  - Many others → e.g. hunger, thirst



Yanan Wang, Judith Amores, and Pattie Maes. 2020. On-Face Olfactory Interfaces. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. ACM, New York, 1–9.

Sensing

- A **just-noticeable difference** (**JND**) is the smallest quantity a user can reliably detect
  - It is also known as a Weber fraction
  - JNDs differ depending on stimuli, such as different haptic textures, force-feedback perception, audio perception, etc.

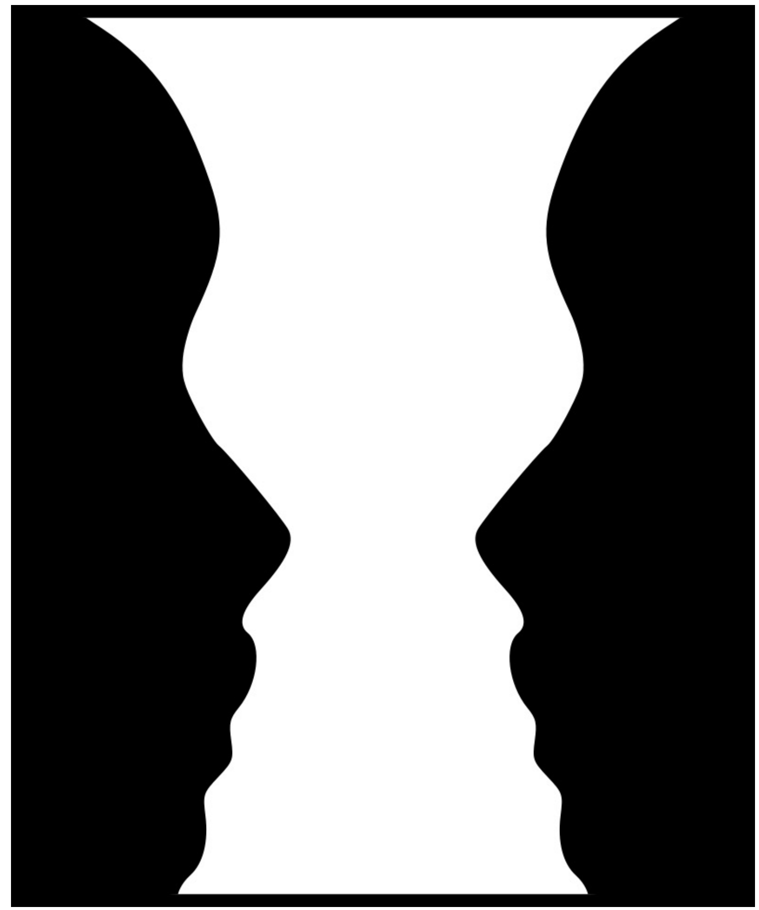


https://en.wikipedia.org/wiki/Weber%E2%80%93Fechner_law#/media/File:Weber-Fechner_law_demo_-_dots.png

Gestalt Psychology and Perception of Form

Figure-ground

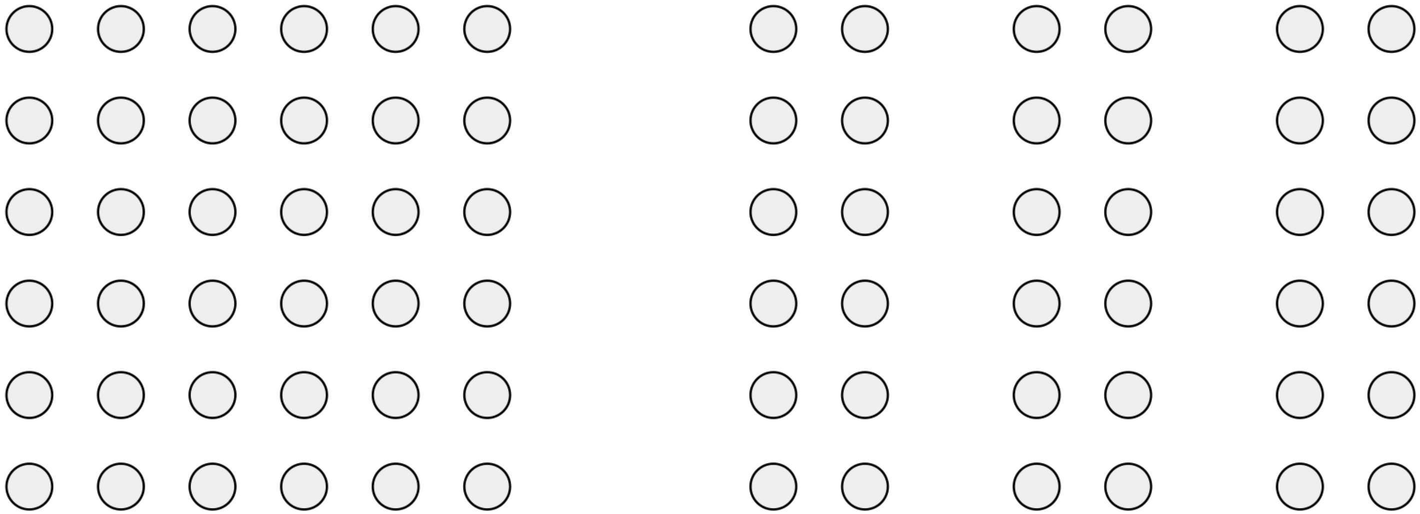
- Separating the figure (the object of interest) against the background
- Critical function for vision



https://en.wikipedia.org/wiki/Figure%E2%80%93ground_(perception)#/media/File:Cup_or_faces_paradox.svg

Proximity

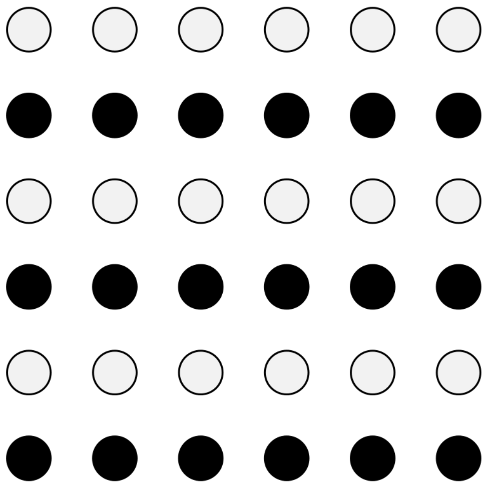
- Objects close together are perceived to be grouped together



https://en.wikipedia.org/wiki/Gestalt_psychology#/media/File:Gestalt_proximity.svg

Similarity

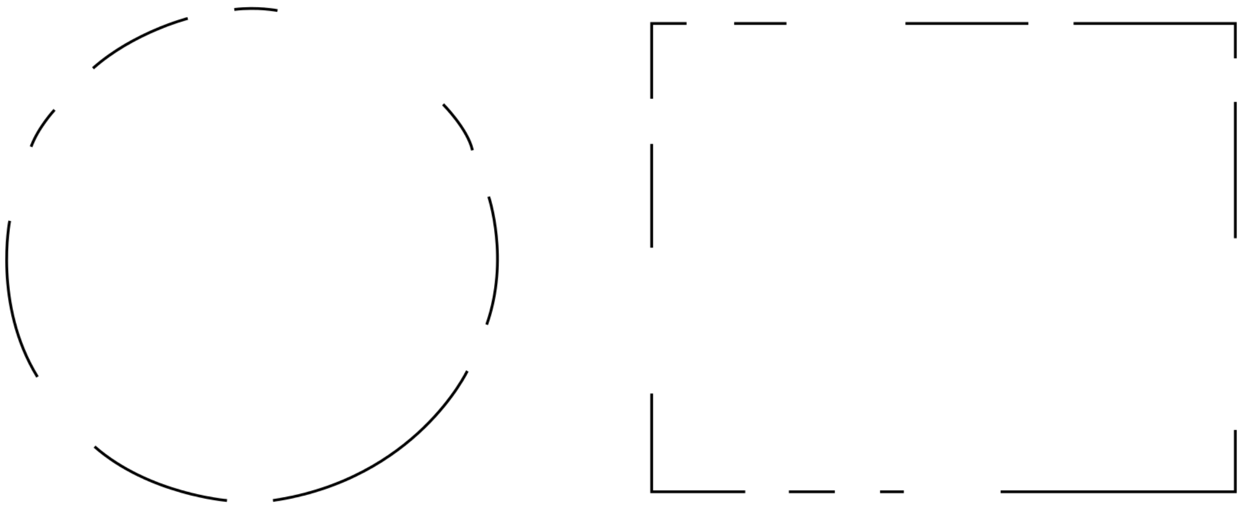
- Objects that appear similar to each other (based on some visual quality such as colour, shape, etc.) are perceived to be grouped together



https://en.wikipedia.org/wiki/Gestalt_psychology#/media/File:Gestalt_similarity.svg

Closure

- Visual objects such as shapes, letters, etc. are perceived to be complete (closed) even though there are gaps
- Gaps are filled in by the visual subsystem



https://en.wikipedia.org/wiki/Gestalt_psychology#/media/File:Gestalt_closure.svg

Symmetry

- Objects are perceived to be symmetrical and formed around a centroid
- Two unconnected visual objects can be perceived as one symmetrical visual object with a common centroid

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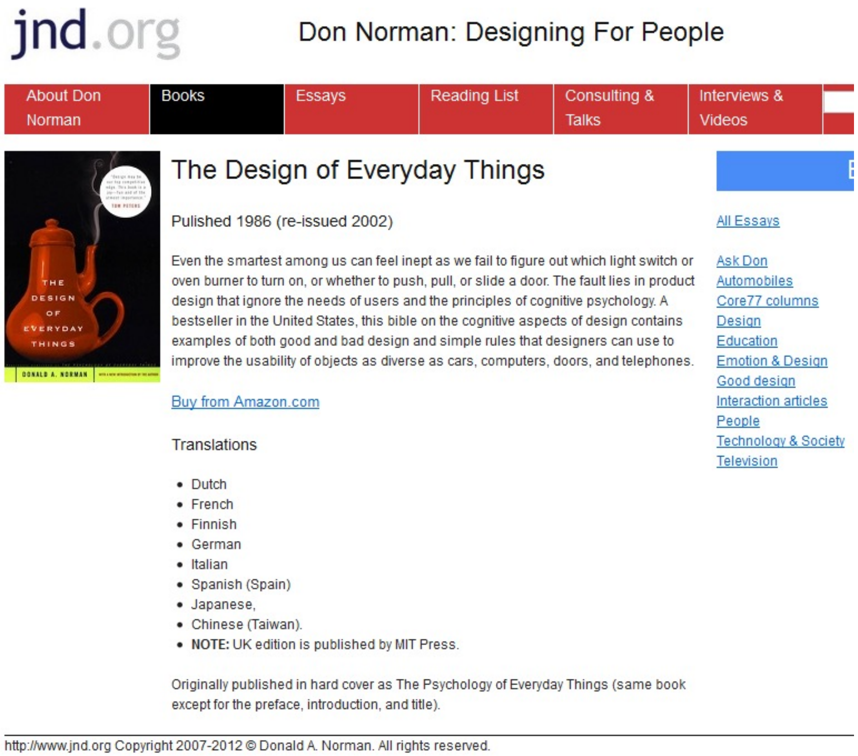
Perceived Affordance

Perceived affordance

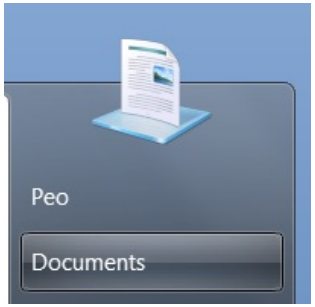
- “Perceived affordance” is a concept introduced by Don Norman in the book “The Design of Everyday Things”
- “In similar vein, because I can click anytime I want, it is wrong to argue whether a graphical object on the screen "affords clicking." It does. The real question is about the perceived affordance: Does the user perceive that clicking on that location is a meaningful, useful action to perform?”

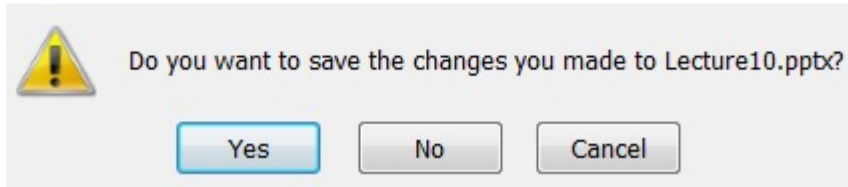
http://www.jnd.org/dn.mss/affordances_and_design.html

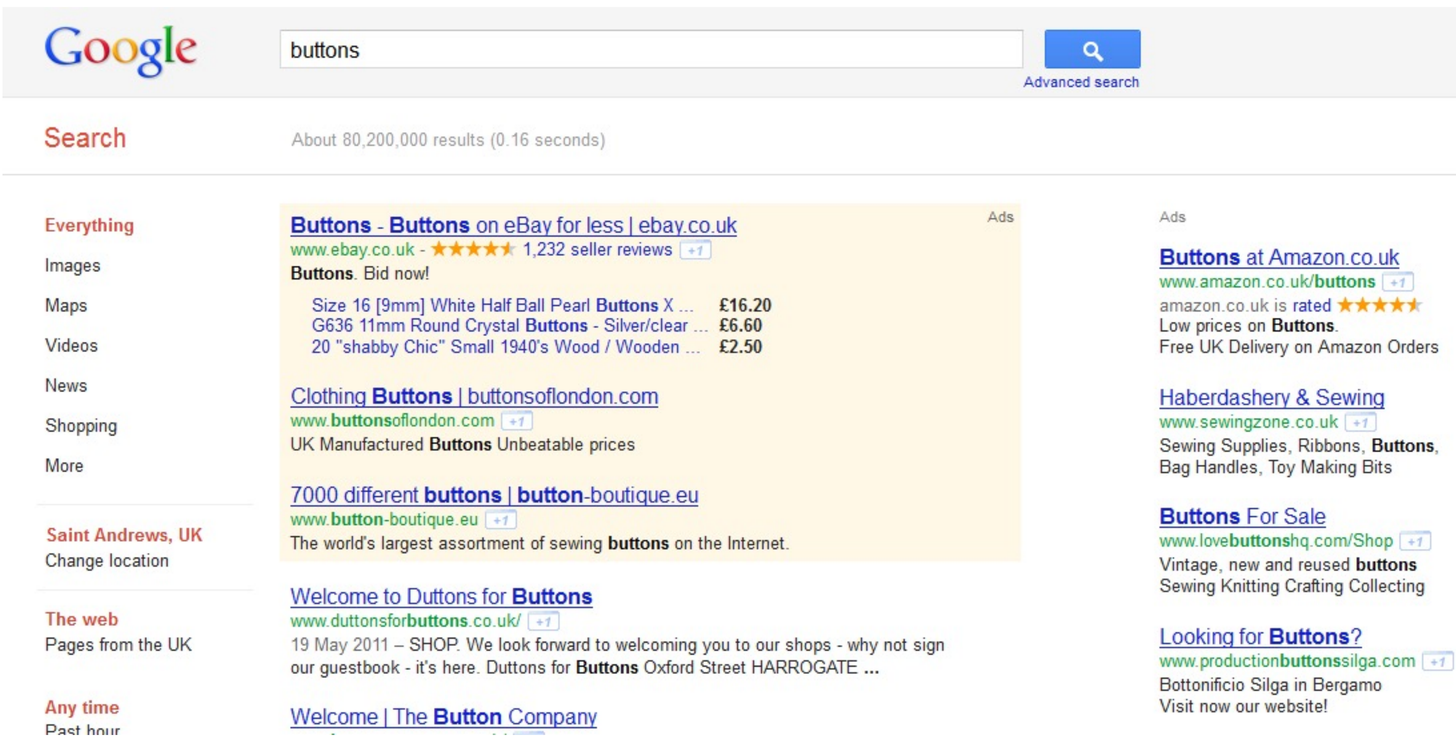


Screenshot from http://www.jnd.org/books/the-design-of-everyday-things.html

Perceived affordance, examples

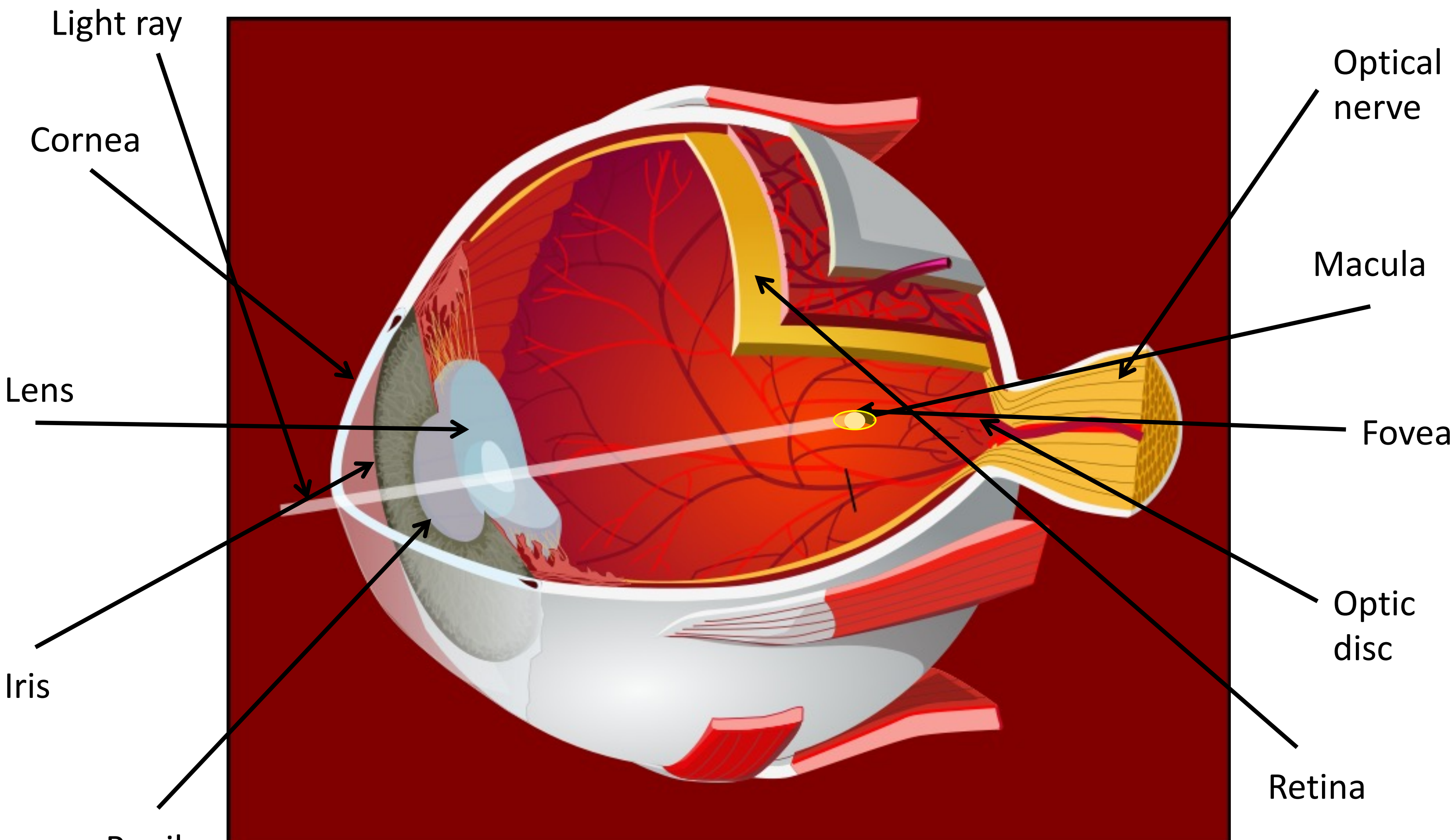






Eye Movement

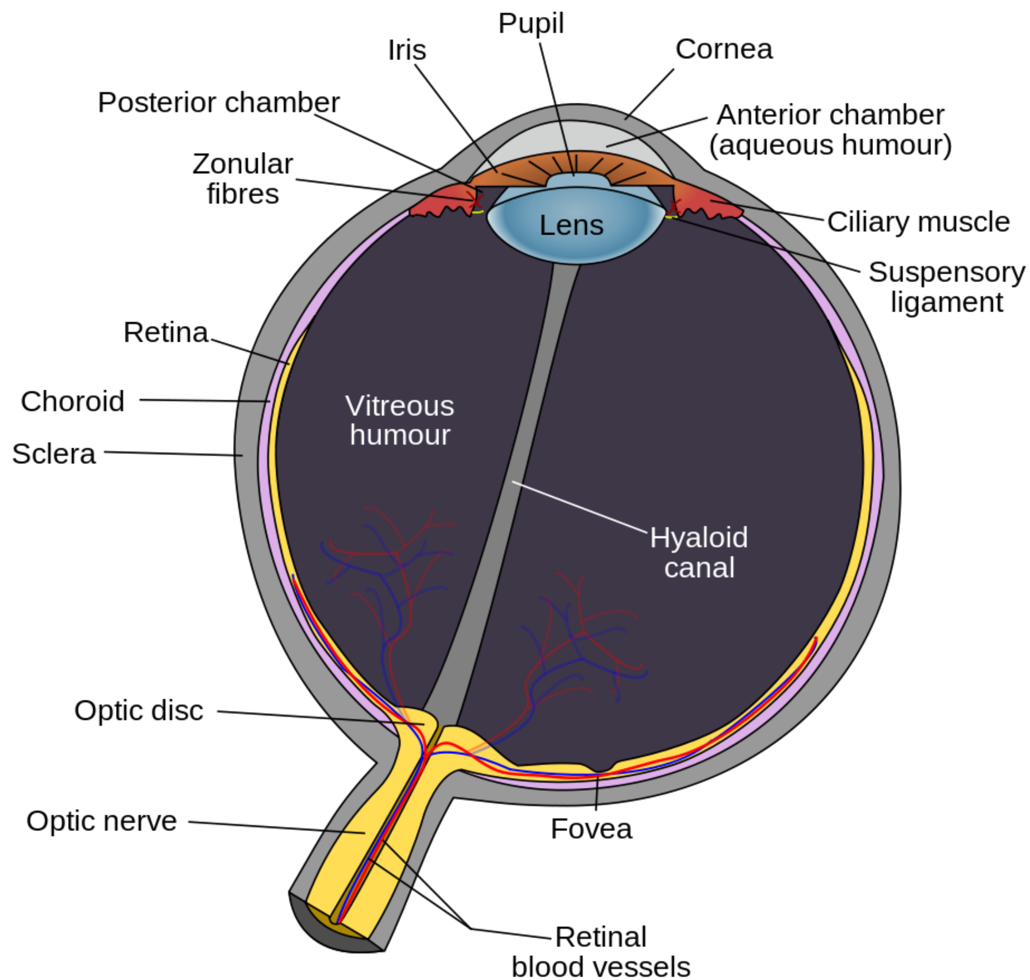
The anatomy of the human eye



http://commons.wikimedia.org/wiki/File:Eye-diagram_bg.svg

Retina, fovea and macula

- The retina converts light into nerve signals
- The macula is an oval yellow spot near the centre of the retina
- The macula is responsible for central vision
- A substantial part of the brain's visual capacity is dedicated to processing visual input from the macula
- The fovea is located near the centre of the macula
- The fovea has a higher concentration of photoreceptors with high acuity (clearness)



http://commons.wikimedia.org/wiki/File:Schematic_diagram_of_the_human_eye_en.svg

Eye-tracking

- Eye-trackers infer where the user is looking at the screen by tracking rotations of the eye, typically using one out of four methods:

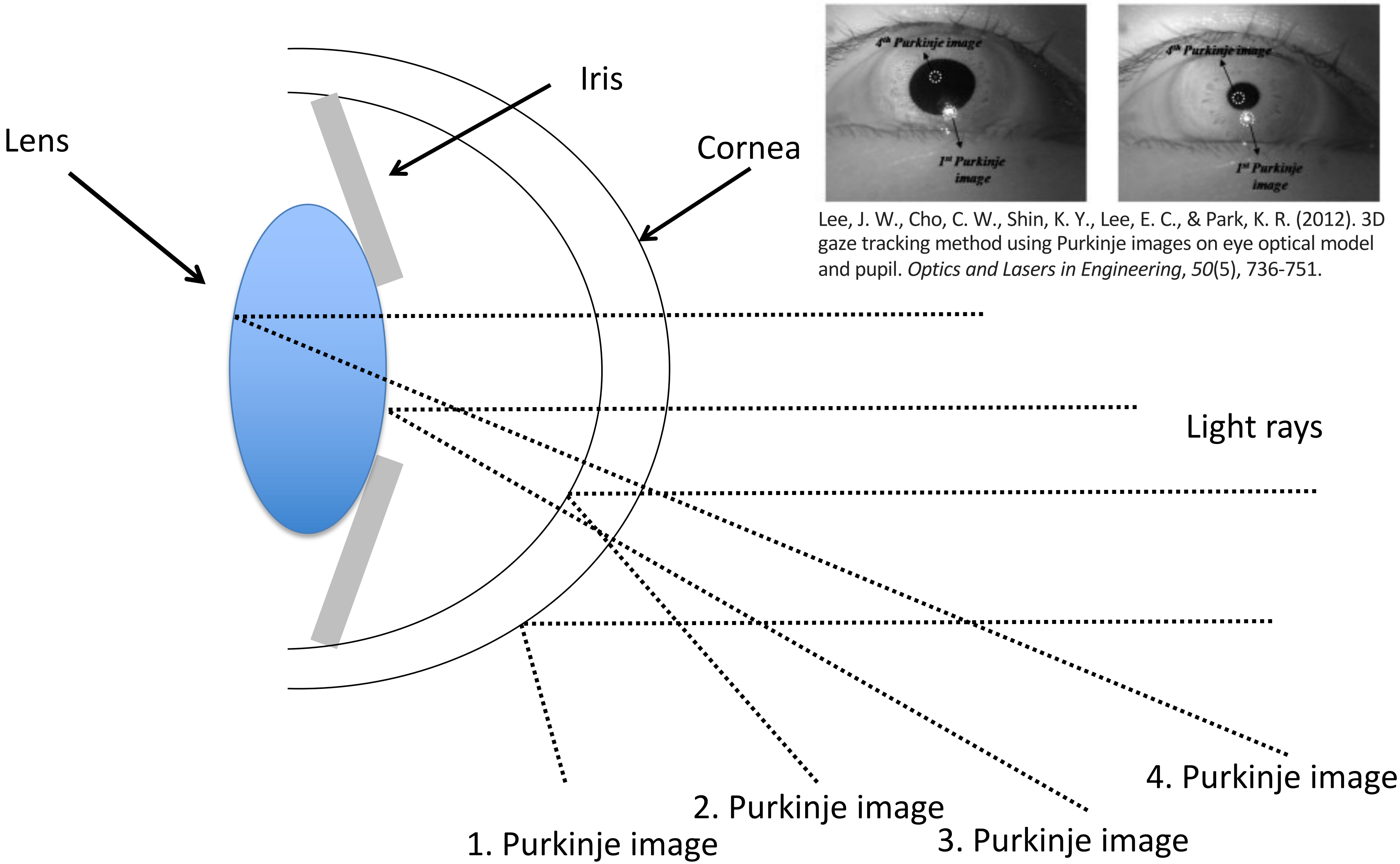
  Projecting infrared light towards the participants' eyes. The anatomical parts of the eye that reflects the light efficiently generate so-called Purkinje images. These images can then be used to infer the user's gaze. High-accuracy commercial eye-tracking systems typically implement some variant of the above or a related scheme. As with all other eye-tracking techniques, this method requires calibration.

  Optically detecting users' gaze via a **regular camera**. Gaze position is inferred via computer vision methods. These methods are very sensitive to users' head movement and as a consequence are not very practical today. Requires recalibration whenever the user is significantly moving their head.

  Electrooculography (EOG). Electrodes are placed above/below or left/right of the eye. The electrodes measure the resting potential of the retina. If the eye is moved away from the centre position towards an electrode then the electrode will sense the change. This information can then be used to infer relative eye position changes. A problem with EOG is drift. A downside is the required set-up before use.

  Contact lenses with some form of sensor, such as a magnetic field sensor. As the eye rotates the contact lens rotates with it. Enables highly accurate eye movement measurements. The downside is that the technique is invasive and requires set-up.

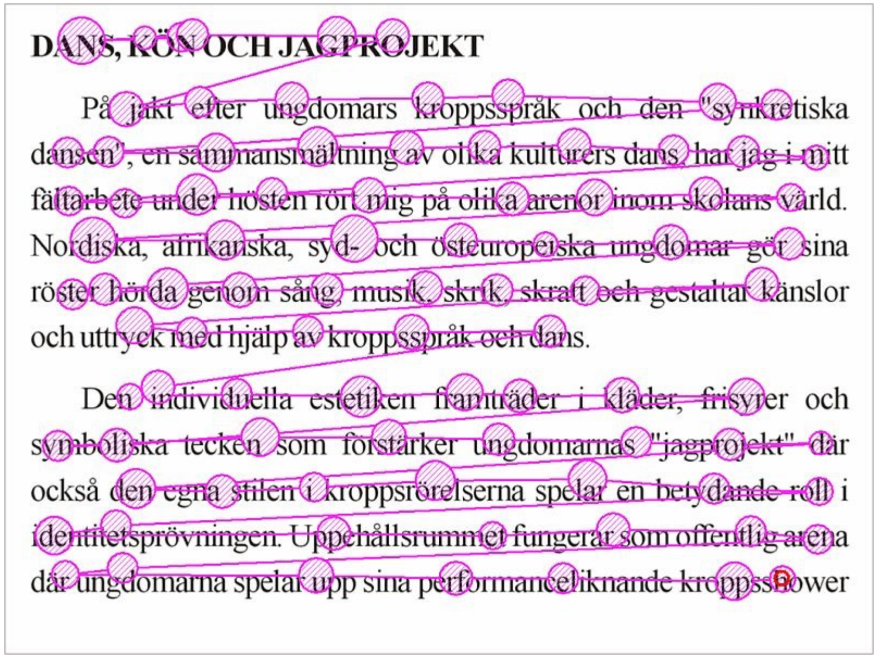
Eye-tracking using Purkinje images



Lee, J. W., Cho, C. W., Shin, K. Y., Lee, E. C., & Park, K. R. (2012). 3D gaze tracking method using Purkinje images on eye optical model and pupil. *Optics and Lasers in Engineering*, *50*(5), 736-751.

Saccades and fixations

- A **saccade** is a ballistic jump
- Saccades are pre-planned and take 150–250 ms to plan and execute
- A saccade ends with a **fixation**
- A fixation is the period of time after a saccade when the eye is relatively stationary (200–300 ms)



http://commons.wikimedia.org/wiki/File:Reading_Fixations_Saccades.jpg

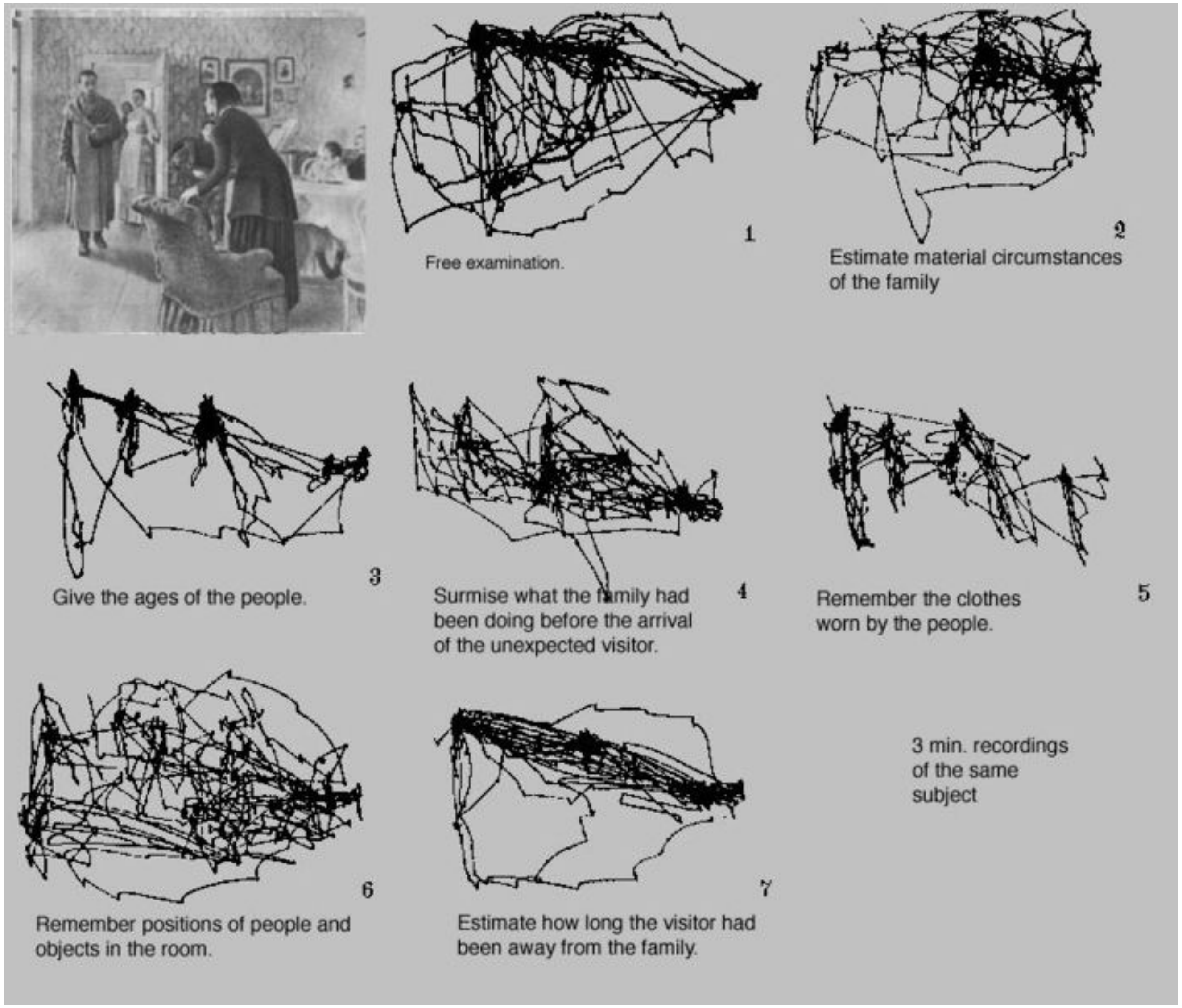
Scanpaths

- A sequence of saccade-fixations forms a **scanpath**
- Such scanpaths can be recorded using eye-tacking technology that records users’ gaze positions at a certain rate (typically 30-60 Hz)
- These scanpaths are then aggregated into fixations if they meet certain time and location thresholds
- The assumption is that if a user has fixated on an area it will influence the user’s further actions or the details that the user is registering in memory
  - However, for this to be likely to be true, the user needs to be given a suitable task

Eye-mind hypothesis

- The **eye-mind hypothesis:**
- *What people look at is what they are thinking about*
- In other words, visual attention is a proxy for mental attention

Yarbus, A. L. (1967). *Eye Movements and Vision*. New York: Plenum.



http://commons.wikimedia.org/wiki/File:Yarbus_The_Visitor.jpg

Change Blindness and Inattentional Blindness

Change blindness and inattentional change blindness

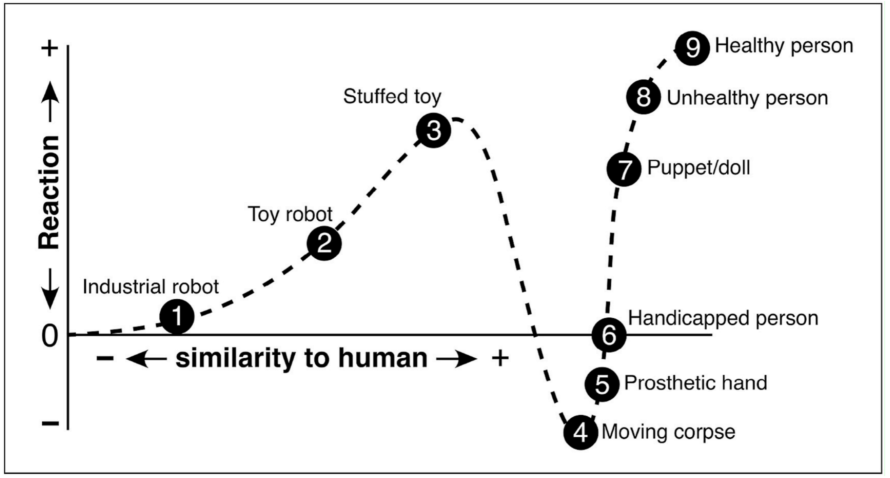
- Change blindness is a failure of a user to detect a visual change in their field-of-view
  - Attention is required to detect changes
- **Inattentional blindness** relates to first-order information: an inability of the user to detect the presence of quantities of information
- **Change blindness** relates to second-order information: transitions between quantities of information
- Change blindness is likely a side-effect of optimisation of the visual system to avoid cognitive overload (Klein et al. 1992)
  - The real world is in constant motion
  - If motion exceeds a threshold it attracts attention
  - As a result, minor changes are ignored, major changes attract attention
  - If a change is below the threshold it does not attract attention: this leads to change blindness

Triggering change blindness

- Obstruct movement of change by a blank screen
- Time the change to coincide with a blink or a saccade (similar effect as above)
- Movement of the eye can be simulated by moving the entire frame at the time of the change
- Divert attention away from the change by random insertion of visual distractors
- Vary camera position to induce many small changes that serve to obscure the actual change
- Gradual changes are harder to detect than instant changes
- Instant changes with random visual distractors are even harder to detect than gradual changes

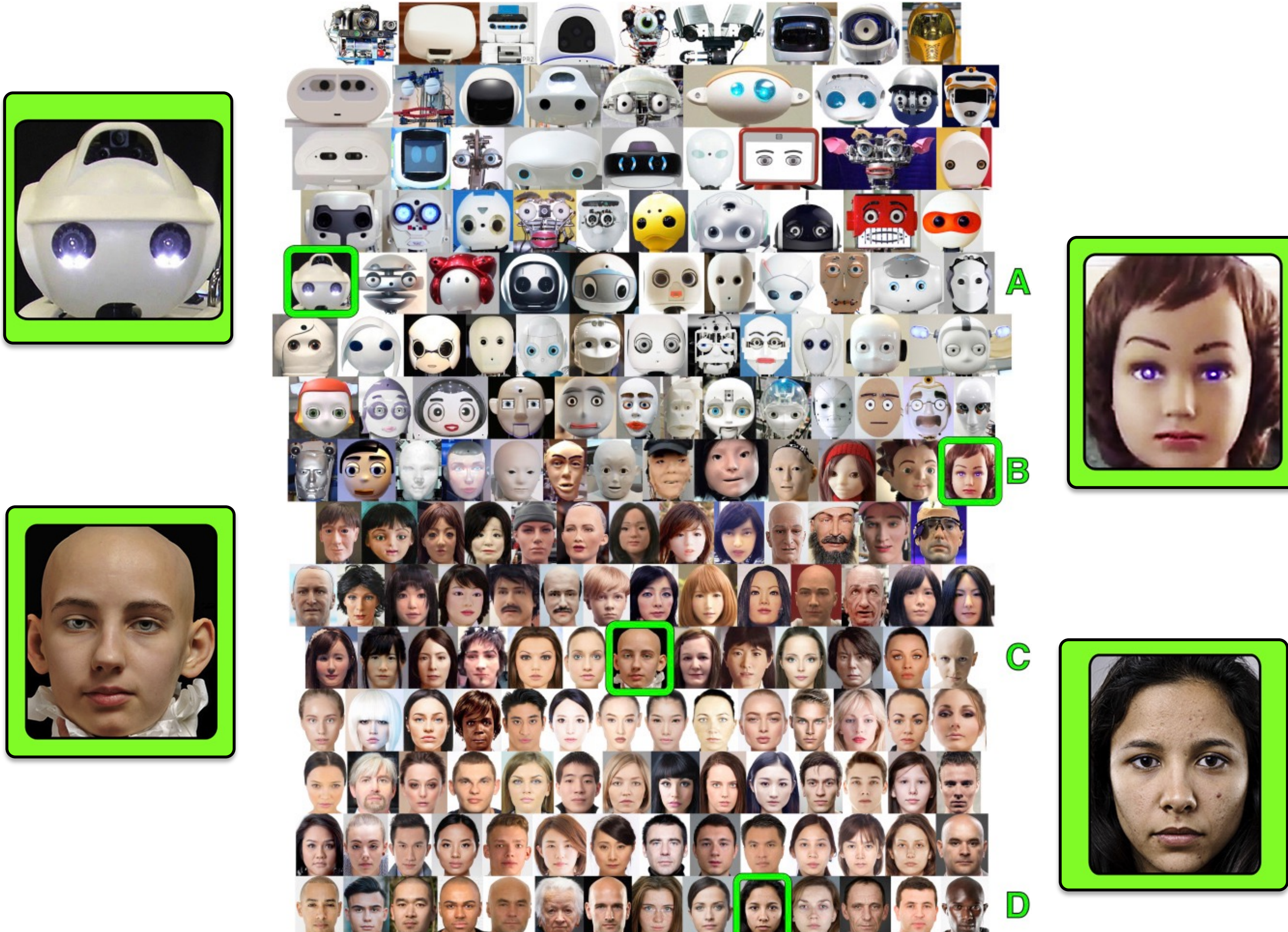
Uncanny Valley

Uncanny valley



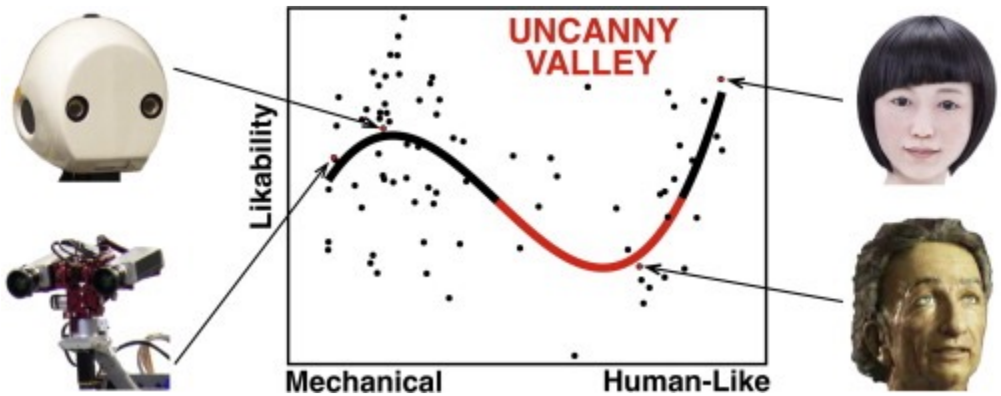
Mathur, M. and Reichling, D.B. 2016 Navigating a social world with robot partners: A quantitative cartography of the Uncanny Valley. Cognition (146): 22-32.

- Theory: users rate robots (or avatars) as increasingly likeable as they approach human similarity until a threshold is reached where users react with strong revulsion; thereafter, as the robot or avatar increases in human similarity, users find the robot or avatar likeable again
  - The interval in human similarity that results in a dramatic decline in positive reactions to the robot or avatar is called the **uncanny valley**
- Originally proposed by Masahiro Mori in 1970
- Has been confirmed in numerous studies



Mathur, M. B., Reichling, D. B., Lunardini, F., Geminiani, A., Antonietti, A., Ruijten, P. A., ... & Aczel, B. (2020). Uncanny but not confusing: Multisite study of perceptual category confusion in the Uncanny Valley. *Computers in Human Behavior*, *103*, 21-30.

Uncanny Valley



Mathur, M. and Reichling, D.B. 2016 Navigating a social world with robot partners: A quantitative cartography of the Uncanny Valley. Cognition (146): 22-32.

- A range of explanations exist: the evocation of corpse-like perception of a near-human; the unattractive traits of a near-human in terms of mating; and pathogen avoidance (near-human possesses inaccurate healthy human characteristics), etc.
- Many critiques: the effect may be cultural/generational (as we get used to robots and avatars the revulsion dissipates); designing in cartoonish or other artistic features can remove the uncanny effect; it is possible to introduce the uncanny to any degree of human likeness; the uncanny effect may be due to multiple factors

Communication

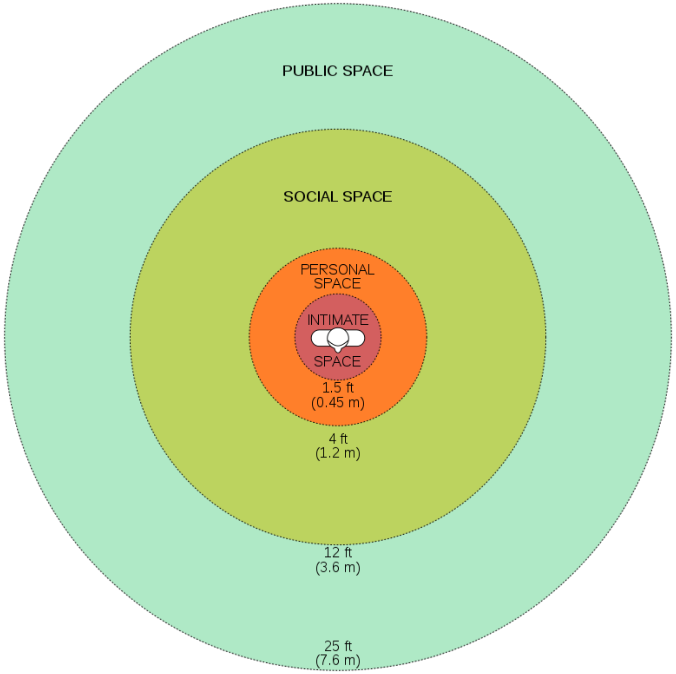
The media equation

- The **media equation** states that people tend to treat computers (and other media) as real people and real places in communication
- For example, people tend to respond to a computer as they would to a person by being polite, cooperative, attributing personality traits, such as aggressiveness, humour, gender, etc.
- There is a large set of different experimental setups confirming this effect (see Reeves and Nass 1996; *The Media Equation* for a comprehensive book summarising the research findings)

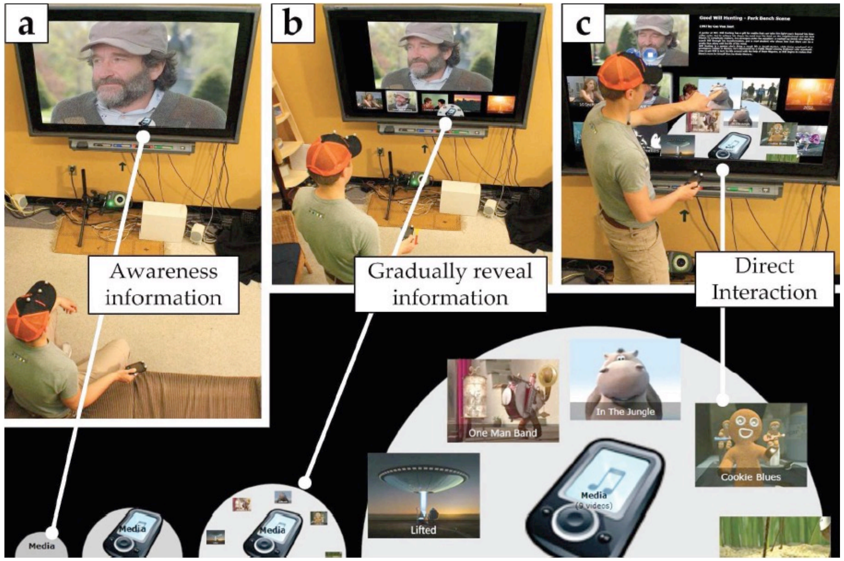
Proxemics

Proxemics

- **Proxemics** is the general study of use of space among humans
- Interpersonal distances describe distances people are comfortable with



https://en.wikipedia.org/wiki/Proxemics#/media/File:Personal_Space.svg



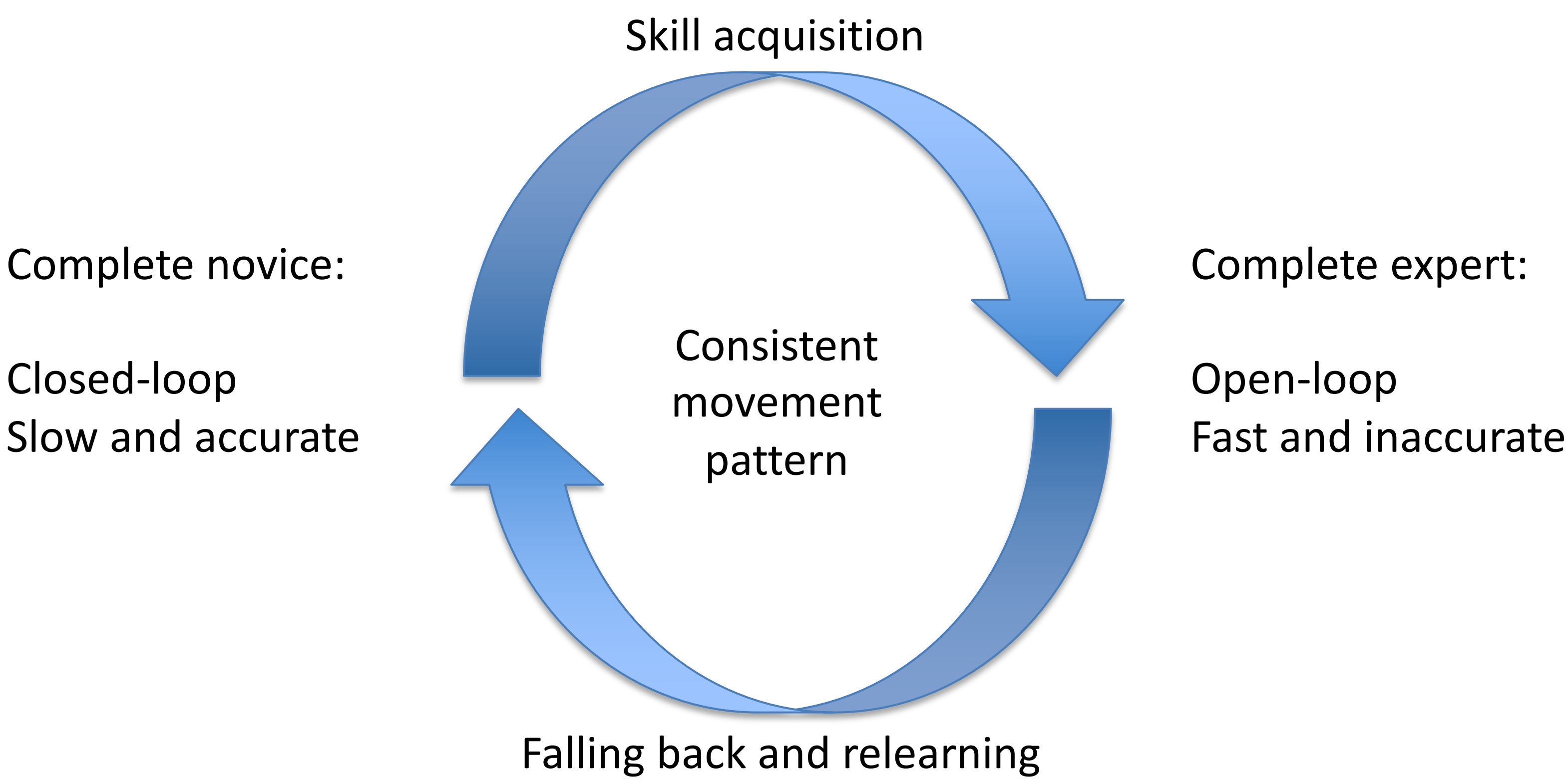
Ballendat, T., Marquardt, N., & Greenberg, S. (2010). Proxemic interaction: designing for a proximity and orientation-aware environment. In *ACM International Conference on Interactive Tabletops and Surfaces* (pp. 121-130).

Motor Control

Closed vs. open-loop interaction

- **Closed-loop interaction**
  - Feedback-guided movement
  - For example: moving a mouse pointer to intersect an icon with the intention to click on it; moving an index finger
  - In general: **slow** and **accurate**
- **Open-loop interaction**
  - Direct recall from motor memory
  - For example: performing a rapid gesture in air
  - In general: **fast** and **inaccurate**

Continuous transition from novice to expert behaviour



Motor memory consolidation

- The automatic and unconscious process in the brain used to store motor routines is known as **motor memory consolidation**
- Several factors influence consolidation, the dominant are:
  - Repetition
  - Sleep
- As a result, for motor skill tasks in experimental settings, it is often useful to space experimental sessions over several days to allow the participant to sleep in between sessions

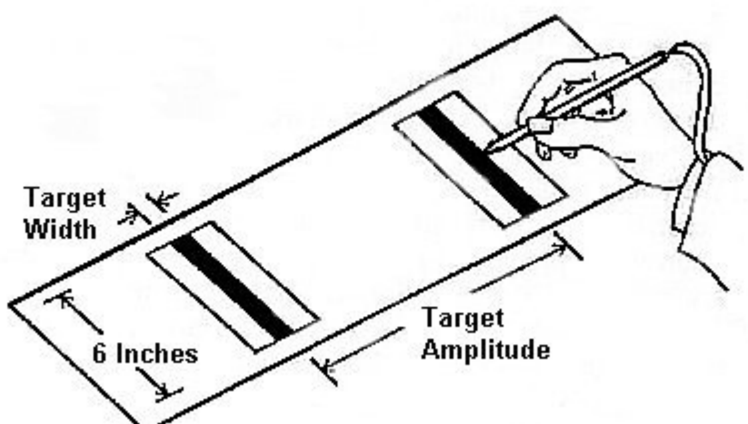
Pointing

Fitts’ law

- Fitts’ law is a mathematical model that predicts that the average movement time required to hit a target along a one-dimensional path is logarithmically proportional to the distance of the target and the width of the target

Fitts’ reciprocal task paradigm

- Fitts’ law is **one dimensional**
- What is meant by the **width** of a target is indicated in the figure below
- Sometimes the **distance** is referred to as **amplitude**



Fitts, P.M. 1954. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology* **47**(6): 381–391.

Fitts' law

- Probably the most well-known and well-established model of human performance
- Models **average movement time** as a function of **index of difficulty**:

$$MT = a + bID$$

where ***a*** and ***b*** are **regression coefficients** and index of difficulty is:

$$ID = \log_2\left(\frac{D+W}{W}\right) = \log_2\left(\frac{D}{W} + 1\right)$$

where ***D*** is the distance to the target and ***W*** is the width of the target

Throughput

- Fitts' law enables us to measure users' **information capacity** via a measure called **throughput**
- Throughput (*TP*) is the number of **bits** of information a user can communicate per second (bits/s) **independently** of a specific target
- One definition of throughput is:

$$TP = \frac{ID_{avg}}{MT_{avg}}$$

- The downside is that this definition is dependent on an arbitrary average ID. An alternative definition of throughput is:

$$TP = \frac{1}{b}$$

- The downside with the latter formulation is that it ignores the effect of *a*.

Fitts' law: assumptions and generalisations

- Fitts' law assumes closed-loop interaction
  - In other words, it models a visually guided action
- Fitts' law only models a particular biologically plausible interval
- The regression coefficients *a* and *b* may vary depending on the task/user/context
- Several generalisations have been investigated, including modelling moving target selection and target selection in 2D

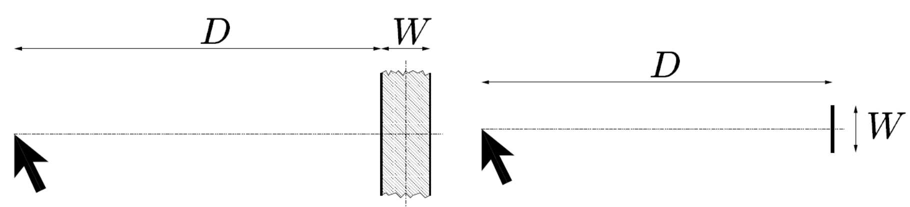
Crossing

Crossing

- A **crossing task** is a target acquisition task relaxes the stopping constraint of a pointing task (the *D* parameter)
- Experimentally, crossing has been demonstrated to adhere to the same mathematical formulation as Fitts' law
- Unlike pointing, crossing allows a user to select multiple targets in a single motion

(a) Pointing a target

(b) Crossing a goal



(a) Pointing: variability is allowed in the direction collinear to movement

(b) Crossing: variability is allowed in the direction orthogonal to movement

Accot, J. and Zhai, S. More than dotting the i's — Foundations for crossing-based interfaces. *Proc. CHI 2002*.

Steering

Steering

- A **steering task** is moving a cursor within a tunnel constraint
  - The literature is messy (original work from 1971 went unnoticed until much, much later), but the foundational paper for human-computer interaction was published at CHI 1997
- In general, the time *T* it takes a user to steer a cursor through a tunnel is:

$$T = a + b\int_C \frac{ds}{W(s)}$$

  - where *a* and *b* are empirically determined parameters, *C* is the tunnel parameterised by *s* and *W*(*s*) is the width of the tunnel at *s*
- Differentiating both sides of the above equation with respect to *s* yields:

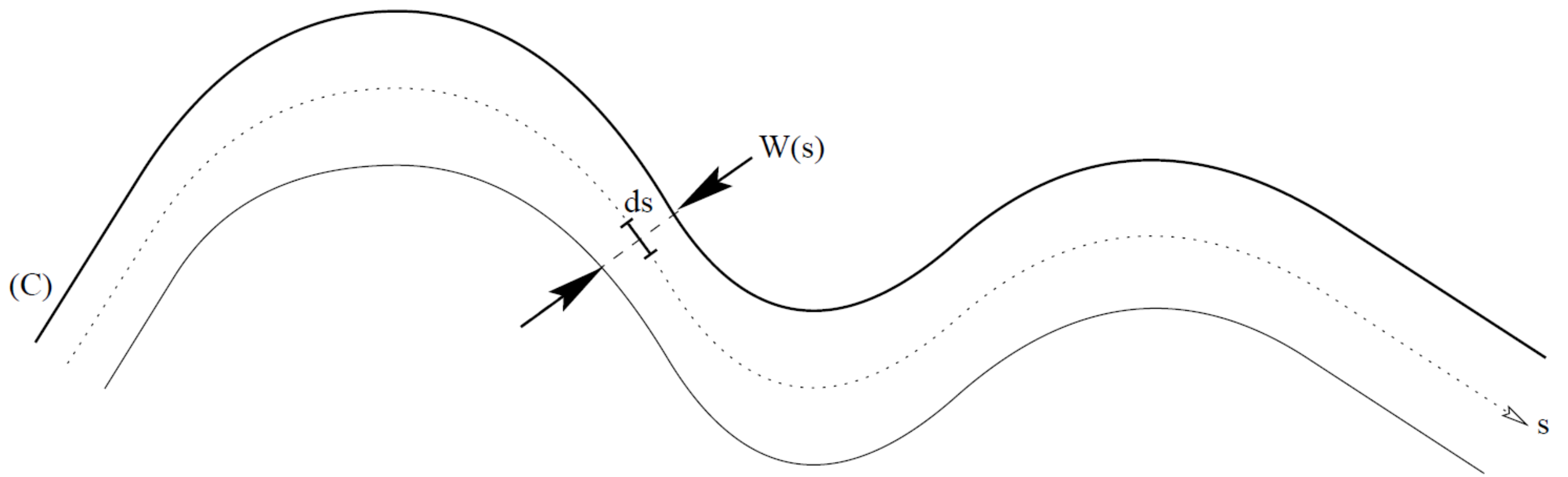
$$\frac{ds}{dT} = \frac{W(s)}{b}$$

  - which confirms that instantaneous movement speed is proportional to the width of the tunnel

Steering

- The index of difficulty for a parameterised curve *C* is:

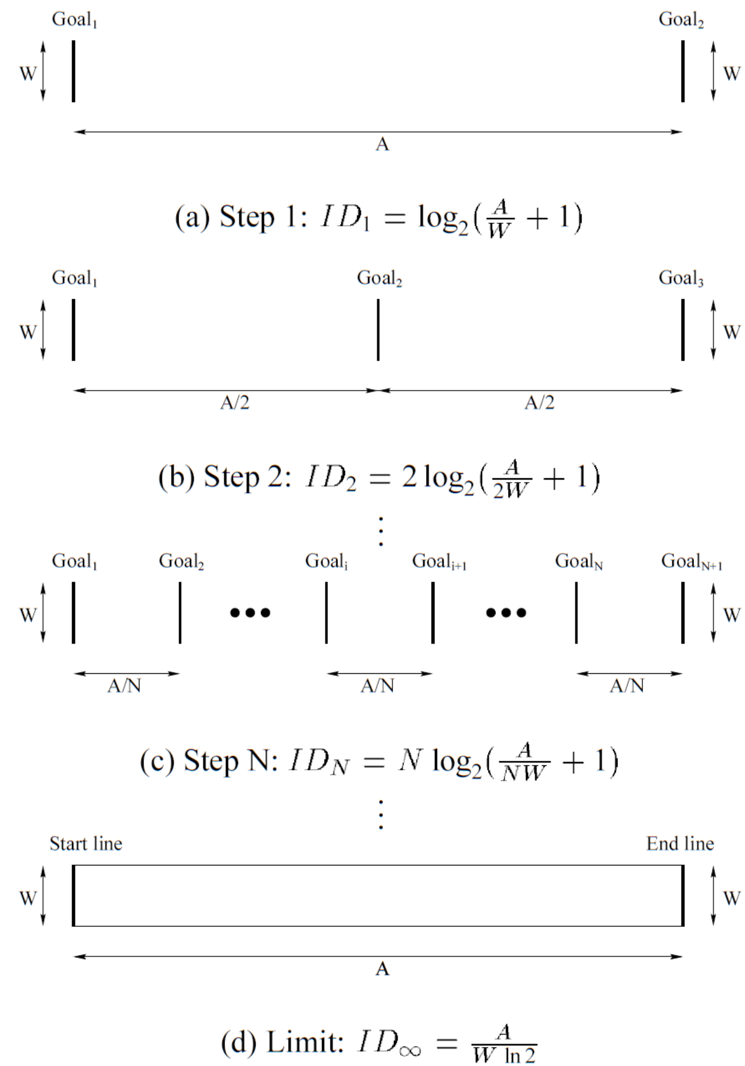
$$ID_C = \int_C \frac{ds}{W(s)}$$



Accot, J. and Zhai, S. Beyond Fitts' Law: Models for Trajectory-Based HCI Tasks. *Proc. CHI 1997*.

Relationship with Fitts' law

- A steering task with constraints on both ends (top left) follows the same logarithmic relationship as Fitts' law
- By generalising the number of N goals the user has to pass through, the constraints form a tunnel constraint
- Note that as N increases, the user has to be more careful in passing through all the goals
- In the limit, the index of difficulty is no longer related to log2(A/W) but to A/W directly
- In other words, in an N goal passing task, as N approaches infinity the difficulty is no longer related to the logarithm of the distance (amplitude; A in the figure) and the width (W)



(a) Step 1: $ID_1 = \log_2(\frac{A}{W} + 1)$

(b) Step 2: $ID_2 = 2\log_2(\frac{A}{2W} + 1)$

(c) Step N: $ID_N = N\log_2(\frac{A}{NW} + 1)$

(d) Limit: $ID_\infty = \frac{A}{W \ln 2}$

Accot, J. and Zhai, S. Beyond Fitts' Law: Models for Trajectory-Based HCI Tasks. *Proc. CHI 1997*.

Cognition

Short-term, long-term and working memory

- **Short-term memory** is the capacity in the brain to store a small amount of information that is in an active and readily accessible format suitable for immediate information processing
  - Miller's famous "The Magical Number Seven, Plus or Minus Two" (1956) article claims the capacity is 7±2 pieces of information (more recent research claims 4±1)
  - Capacity can be increased by **chunking** (organising pieces of information into meaningful groups)
  - Average store time is approximately between 10 and 20 seconds and can be extended by conscious rehearsal of information
- **Long-term memory** is memory devoted to storing information indefinitely
- **Working memory** refers to brain circuitry used for storing and manipulating information

Procedural and declarative memory

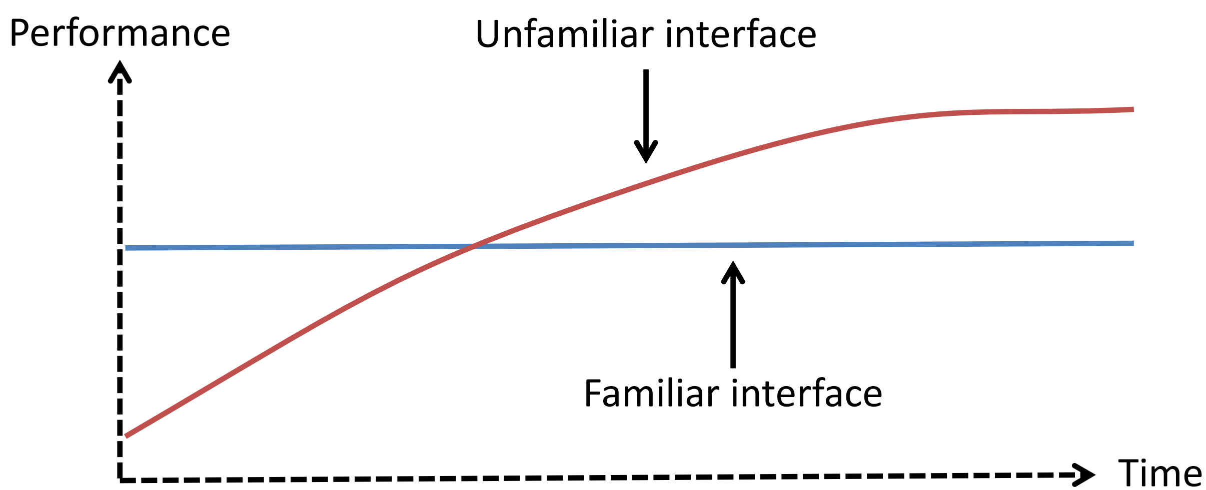
- **Procedural memory** is implicit memory that is unconsciously and involuntary stored in the brain
  - Procedural memory stores routines that are frequently used and can be recalled without conscious awareness
  - Procedural memory is built-up by procedural learning (skill acquisition)
- **Declarative memory** in contrast, stores persons, events, facts, etc.
- Working memory is currently understood to process procedural and declarative memory in separate brain pathways

Skill acquisition

- **Skill acquisition** refers to the ability to acquire routines in procedural memory
- **Practice** is repeating a task
- **Learning** is the result of an observed behavioural change as a result of practice or experience
  - Unlike practice, learning is not directly observable
- Fitts (1954) model of skill acquisition identifies three phases:
  1. Cognitive phase: breaking down a skill into its individual parts and learning them individually; the way the parts relate to the skill is known as **schemas**. This phase demands intensive attention.
  2. Associate phase: Repeated practice of the skill by responding to stimuli until patterns build up in the brain. A critical aspect is identifying relevant stimuli. The more stimuli in the skill, the longer this phase may take.
  3. Autonomous phase: Perfecting the skill by optimising the ability to discriminate between relevant and irrelevant stimuli and automating parts of the thought process (reaching automaticity).
- Alternative models also exist, such as 1) attempt; 2) fail; 3) analyse the result; and 4) change the next attempt (where steps 3 and 4 are implicit)

Power law of practice

- The **power law of practice** is the observation of what is generally called a **learning curve**



- It is possible to overcome stagnation by showing a user new ways of acquiring a skill

Reaction Time and Decision Time

Reaction time vs. decision time

- **Reaction time** is the time it takes a user to respond to a stimulus (a stimulus-response task)
  - For example: push a physical button when the light bulb in front of you turns on
- **Decision time** is the time it takes for a user to make a decision about responding to a stimulus
- Franciscus Donders (1818-1889) is credited to be the first scientist to use the difference between reaction time and decision time (choice reaction time) to investigate human cognitive processing

Open-loop decision time among *n* choices

- A user is presented with *n* choices and **does not need to linearly scan the choices** (i.e. open loop task)
- The classic finding is that the time *T* it takes a user to make such a choice is:
  - $T = bH$
  - where *b* is an empirically determined parameter and *H* is the entropy inherent in the decision:

$$H = \sum_{i=1}^{n} p_i \log_2\left({}^{1}\!/_{p_i} + 1 \right)$$

  - where p_i is the probability of the *i*th choice

- If all choices are equally likely, the expression above reduces to the classic **Hick-Hyman law:**
  - $T = b \log_2(n + 1)$
  - where *n* is the number of choices and *b* is an empirical parameter
- The Hick-Hyman model is approximate only (it is possible to obtain a better fit by a sigmoid rather than a linear function) and only applies when the user can engage in a divide-and-conquer strategy for making their choice

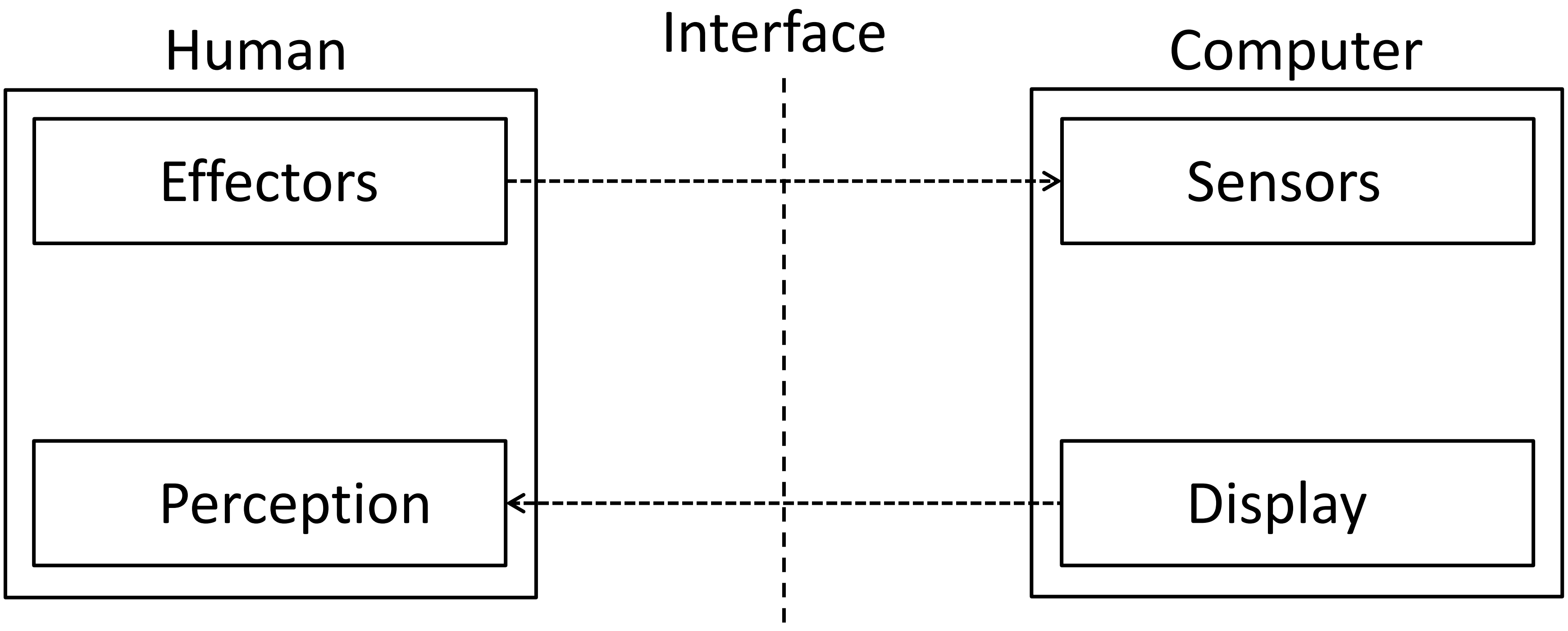
Control

Unless otherwise noted, this part of the lecture is based on: Murray-Smith, R. 2018. Control theory, dynamics and continuous interaction. In Oulasvirta, A., Kristensson, P.O., Bi, X. and Howes, A. (Eds.), *Computational Interaction*. Oxford: Oxford University Press, 17-41.

Control

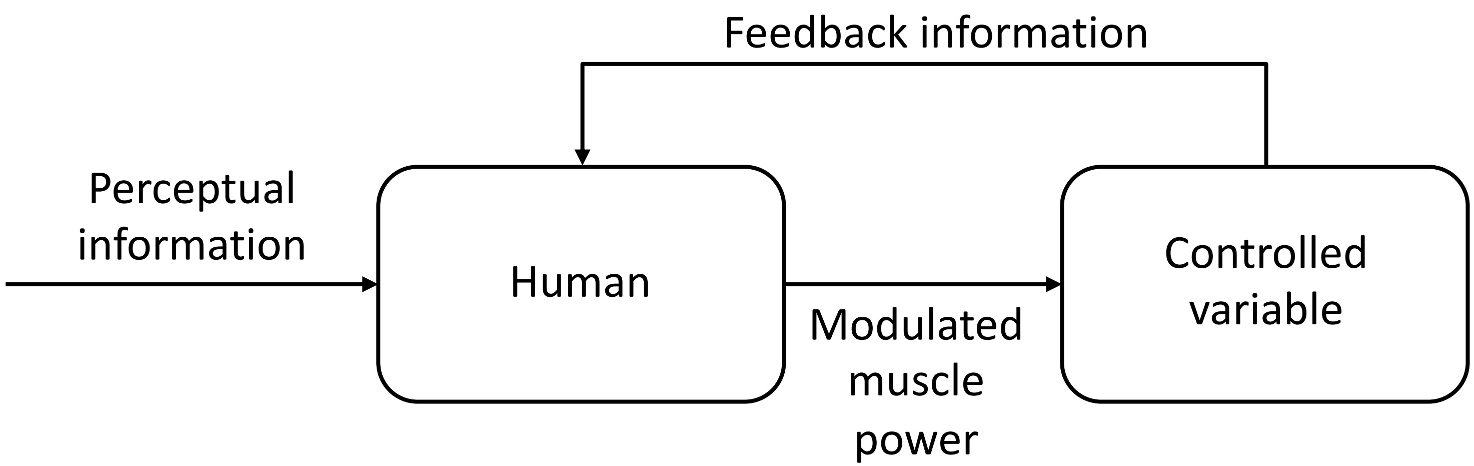
- Traditionally, HCI theory has viewed human-computer interaction as **communication of information** (bits transmitted over a noisy channel)
- However, our bodies move continuously in space and time in order for our intentions to be sensed by sensors and interpreted by a machine
  - Such continuous movement is guided by feedback
  - It follows that any model of human-computer interaction has to be underpinned by a notion of continuous control
- Second, often the objective of the user is to **control** some aspect of an artefact or the environment

Human-computer interaction as a closed-loop system

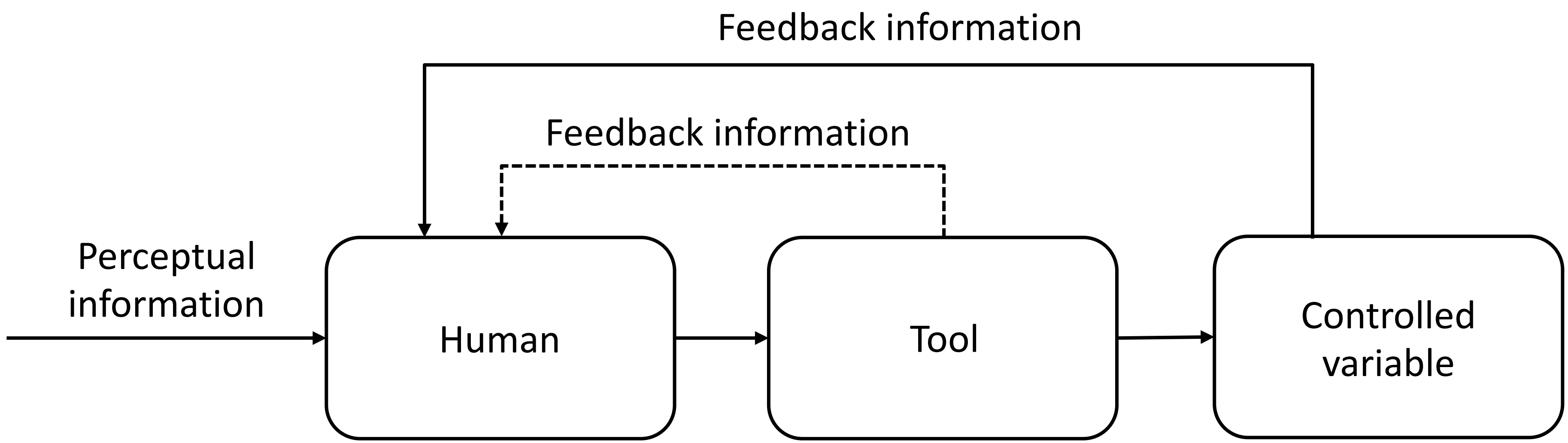


- Analysis of how a joint human-computer system performs as opposed to analysis of communication between the parts

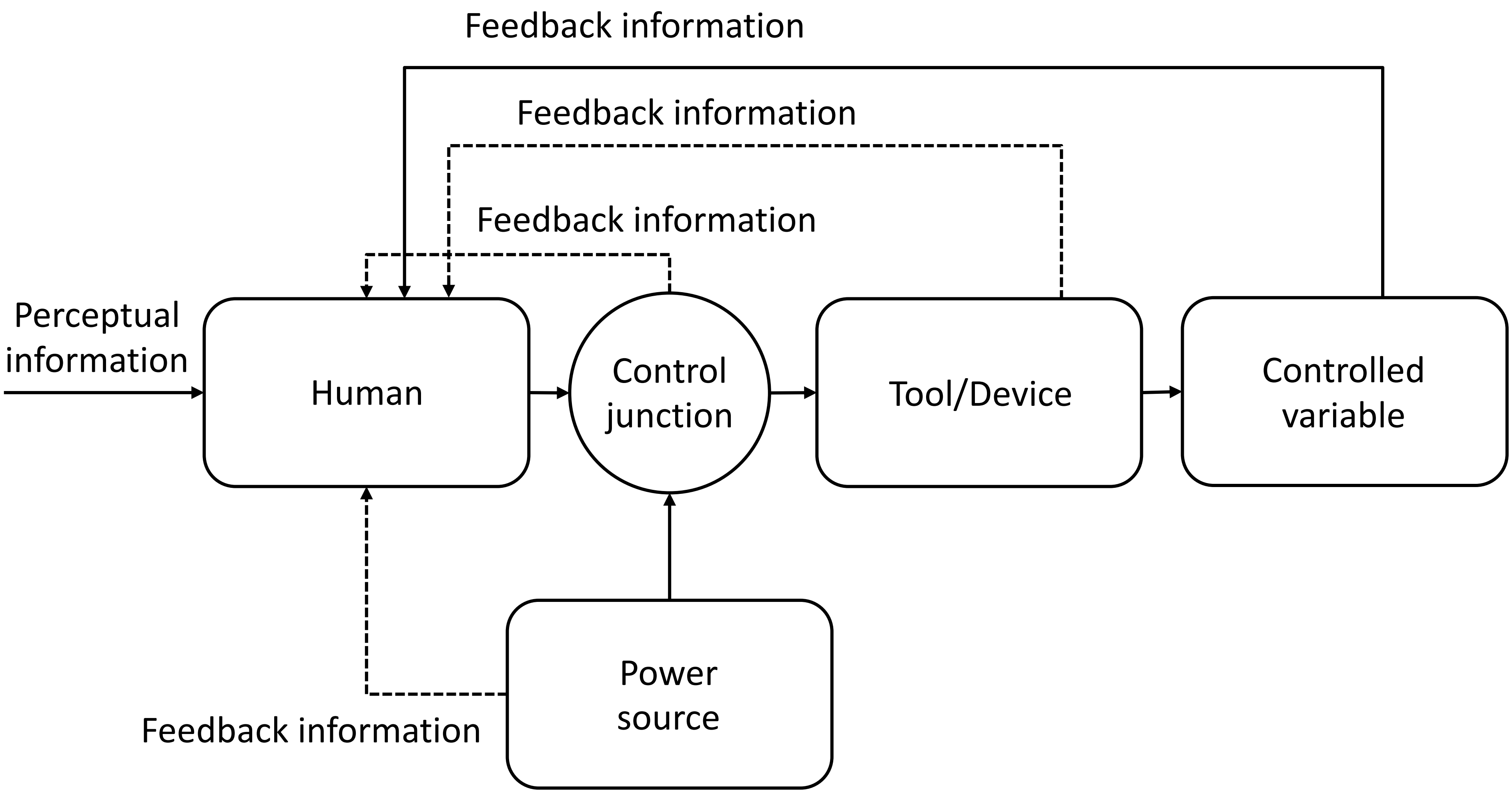
Control models of interaction: direct muscle power



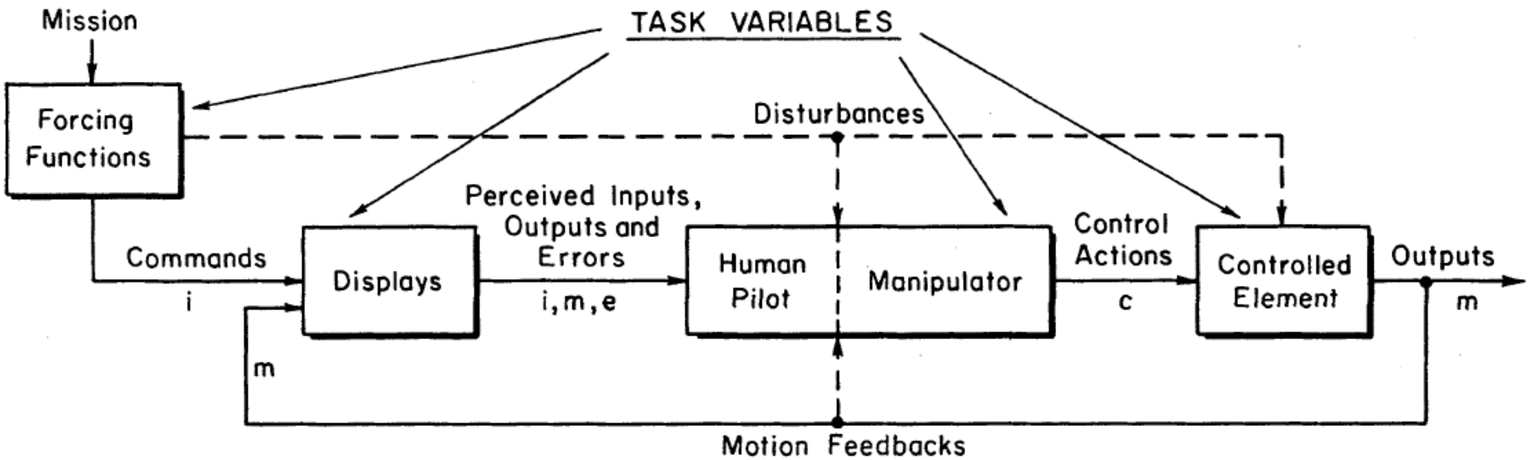
Control models of interaction: use of specialised tools for specific tasks



Control models of interaction: externally powered devices, potentially regulated by automatic controllers



Pilot models

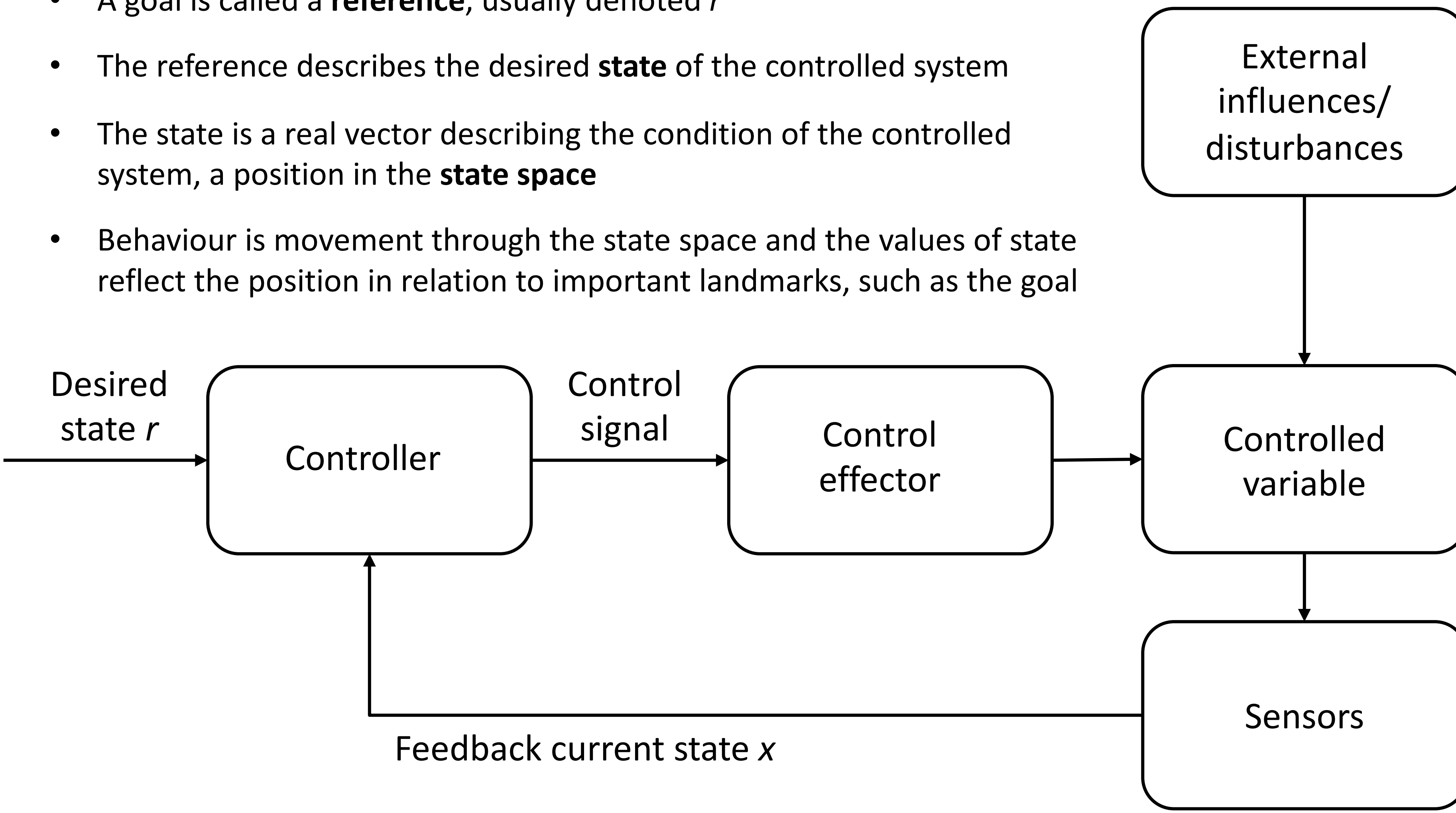


ENVIRONMENTAL VARIABLES:	OPERATOR-CENTERED VARIABLES:	PROCEDURAL VARIABLES:
In-Flight vs. Fixed-Base	Motivation	Instructions
Vibration	Stress	Practice
G-Level	Workload	Experimental Design
Temperature	Training	Order of Presentation
Atmospheric Conditions	Fatigue	Etc.
Etc.	Etc.	

McRuer, D. T., & Jex, H. R. (1967). A review of quasi-linear pilot models. *IEEE transactions on human factors in electronics*, (3), 231-249.

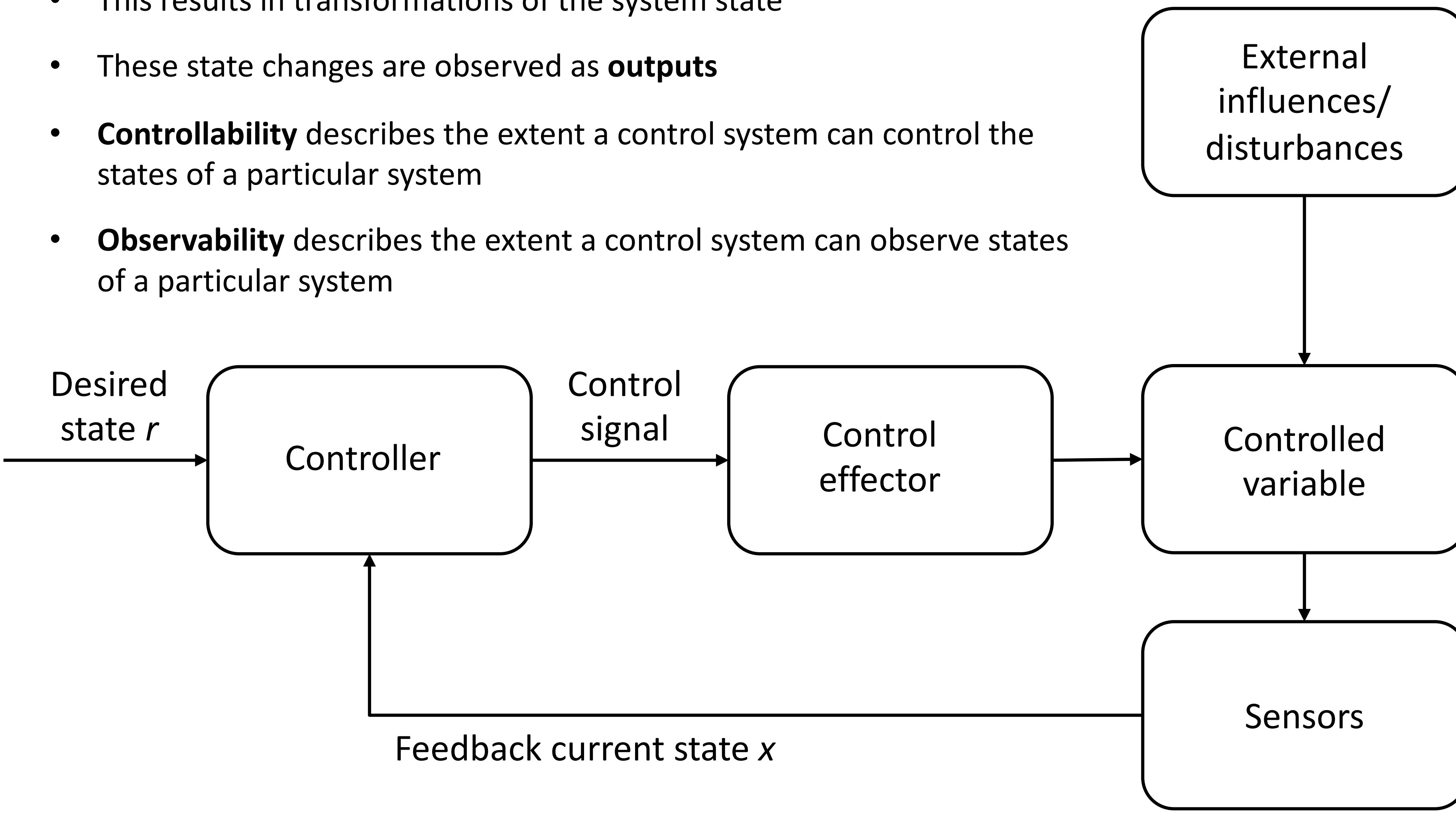
Classic control loop

- The output of every block is time varying (dynamic system)
- A goal is called a **reference**, usually denoted *r*
- The reference describes the desired **state** of the controlled system
- The state is a real vector describing the condition of the controlled system, a position in the **state space**
- Behaviour is movement through the state space and the values of state reflect the position in relation to important landmarks, such as the goal



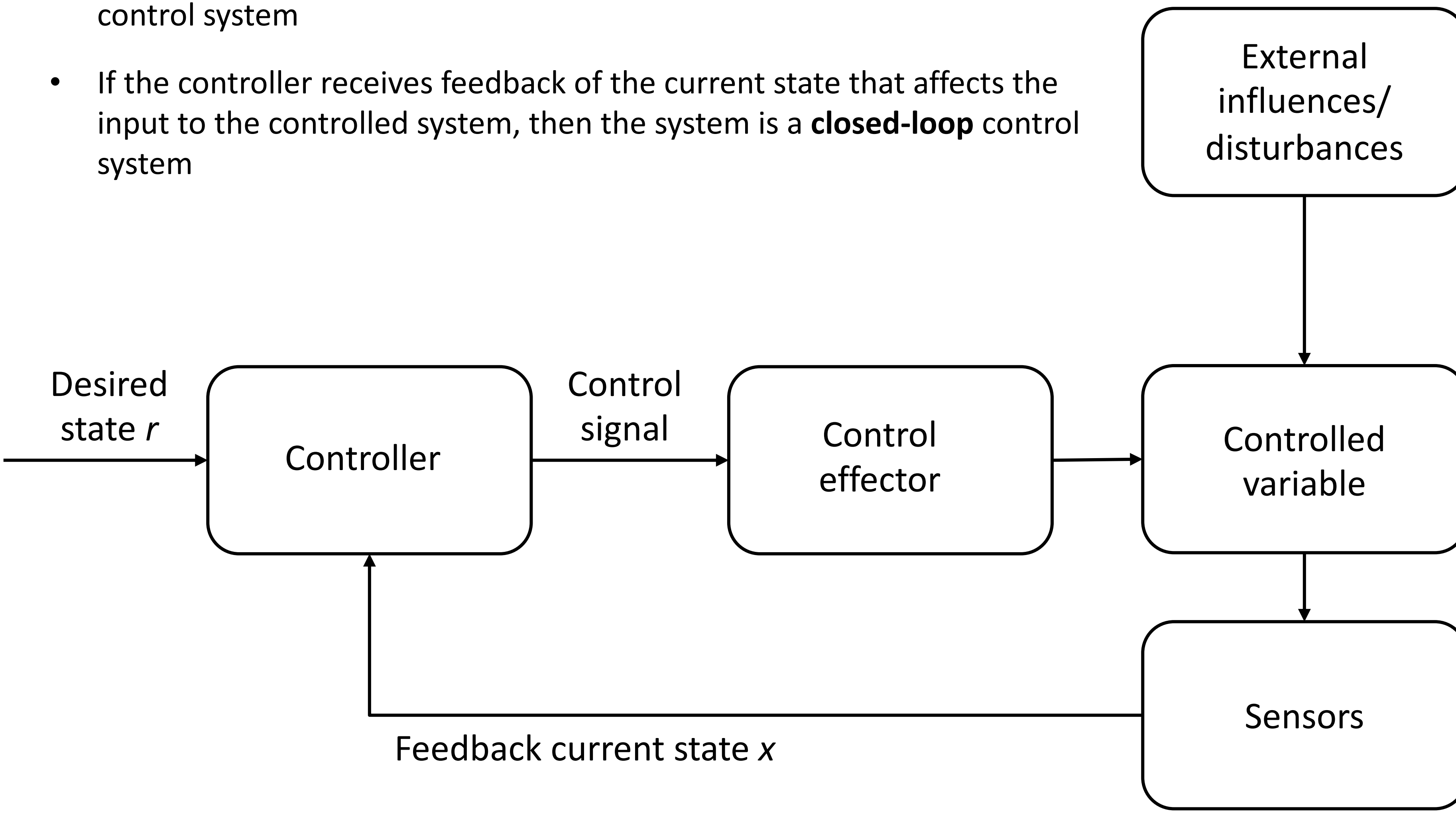
Classic control loop

- The **controller** generates control inputs to the controlled system
- This results in transformations of the system state
- These state changes are observed as **outputs**
- **Controllability** describes the extent a control system can control the states of a particular system
- **Observability** describes the extent a control system can observe states of a particular system



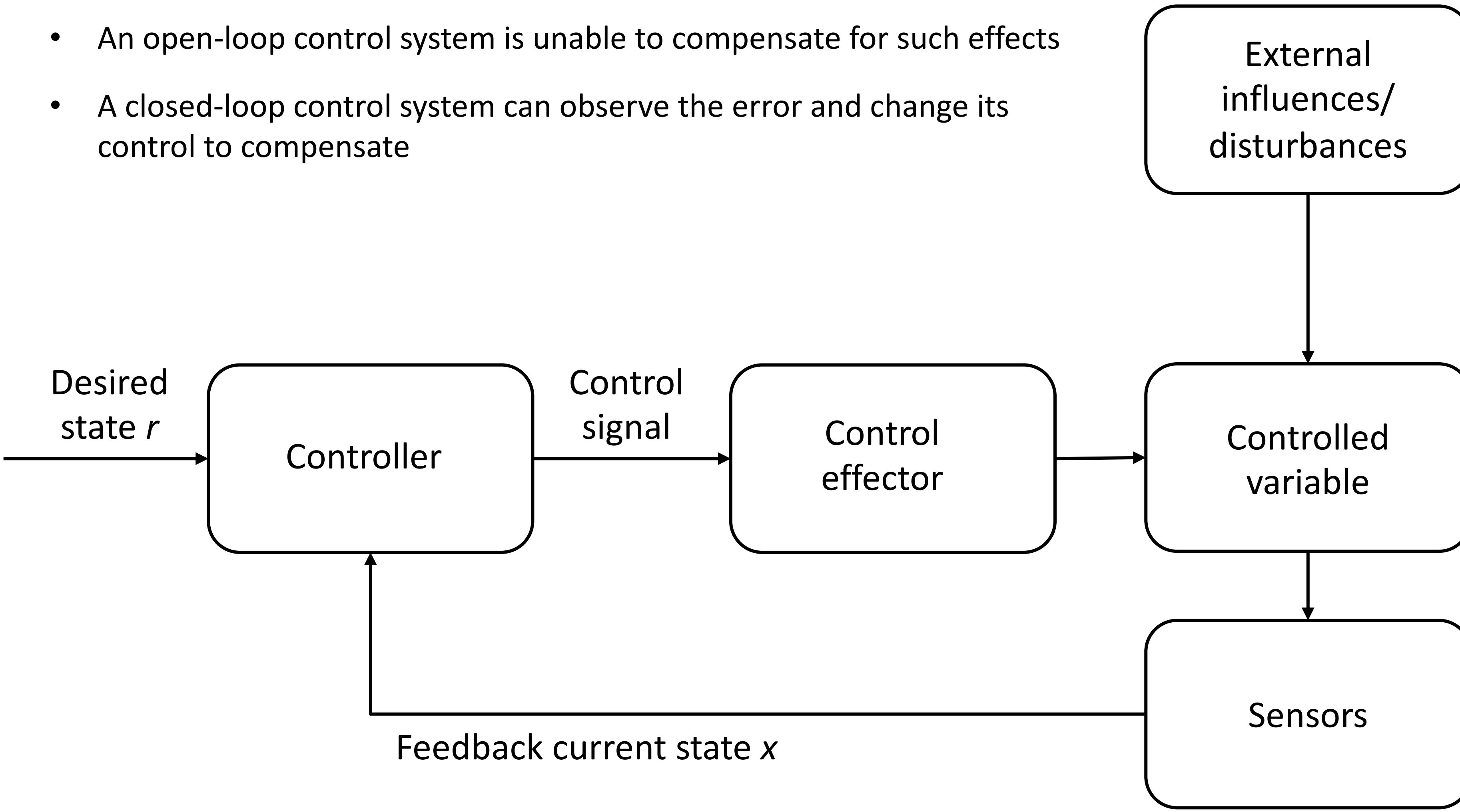
Classic control loop

- If an input is transformed but the control variable is independent of feedback from the system state, then the system is an **open-loop** control system
- If the controller receives feedback of the current state that affects the input to the controlled system, then the system is a **closed-loop** control system



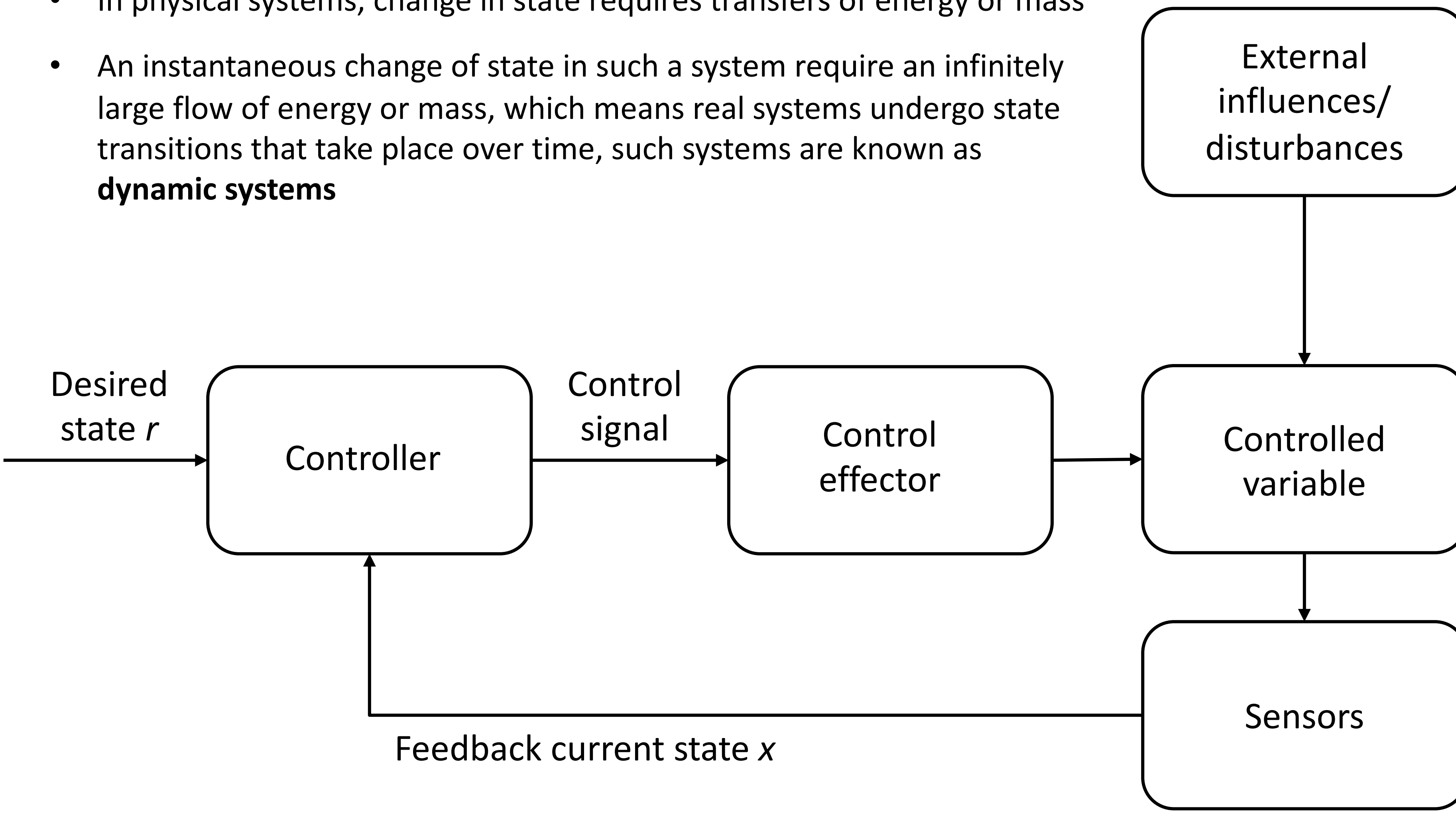
Classic control loop

- External or unpredictable effects that affect a system state are known as **disturbances**
- An open-loop control system is unable to compensate for such effects
- A closed-loop control system can observe the error and change its control to compensate



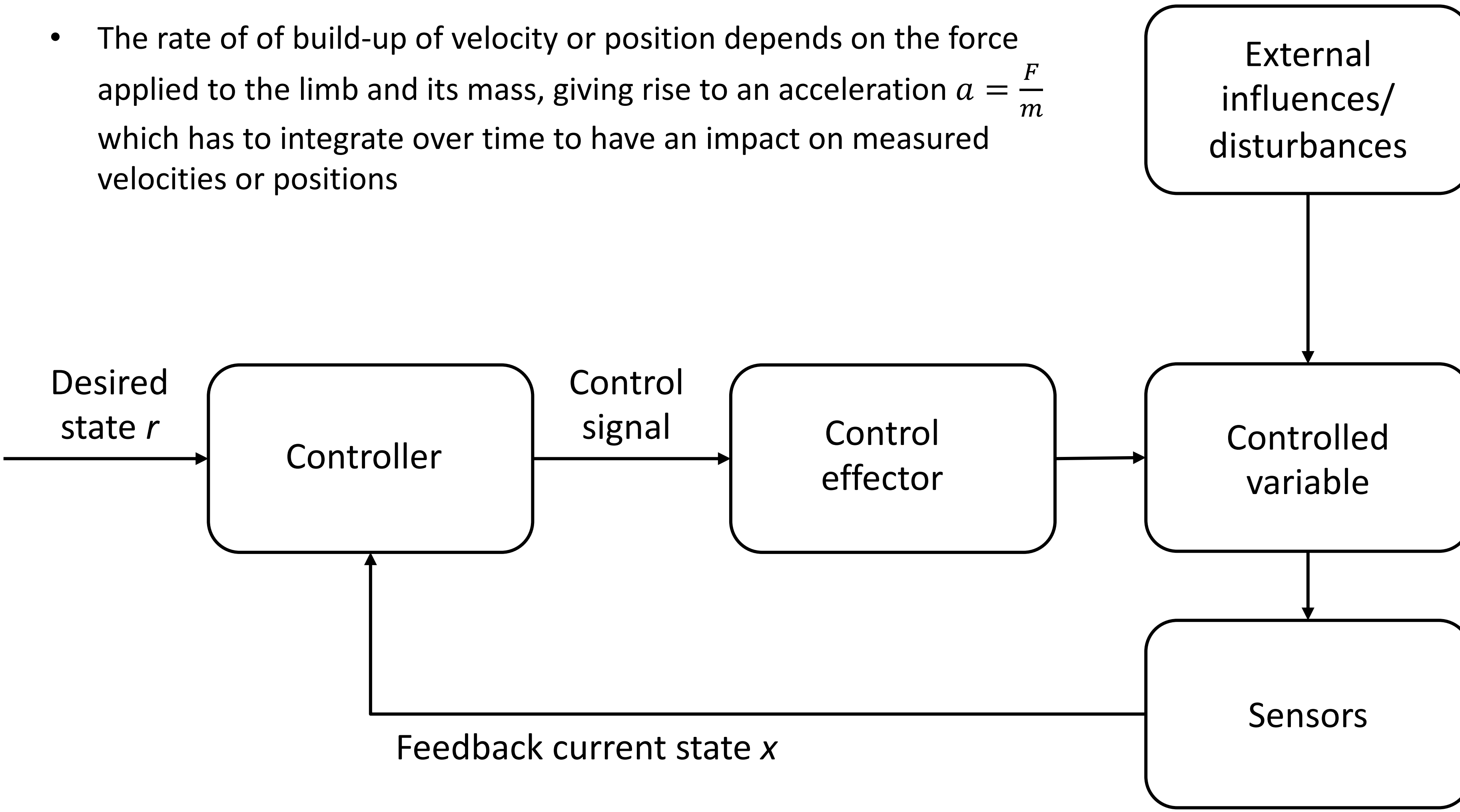
Classic control loop

- **Dynamics** describe how the system responds over time
- In physical systems, change in state requires transfers of energy or mass
- An instantaneous change of state in such a system require an infinitely large flow of energy or mass, which means real systems undergo state transitions that take place over time, such systems are known as **dynamic systems**



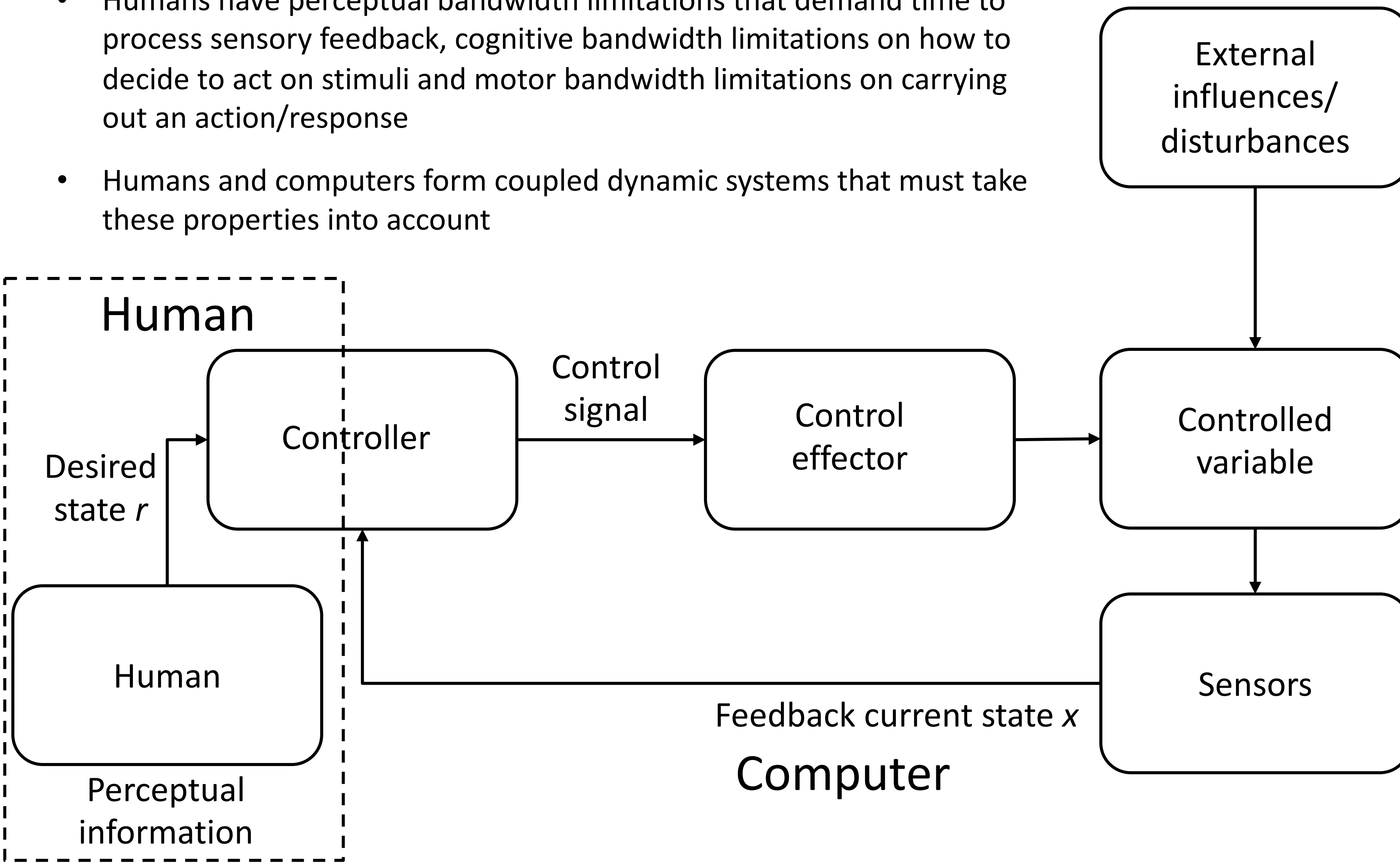
Classic control loop

- Human effectors, such as an arm or finger for pointing, have mass and a system with mass cannot instantaneously achieve high velocity
- The rate of of build-up of velocity or position depends on the force applied to the limb and its mass, giving rise to an acceleration $a = \frac{F}{m}$ which has to integrate over time to have an impact on measured velocities or positions



Human-computer control loop

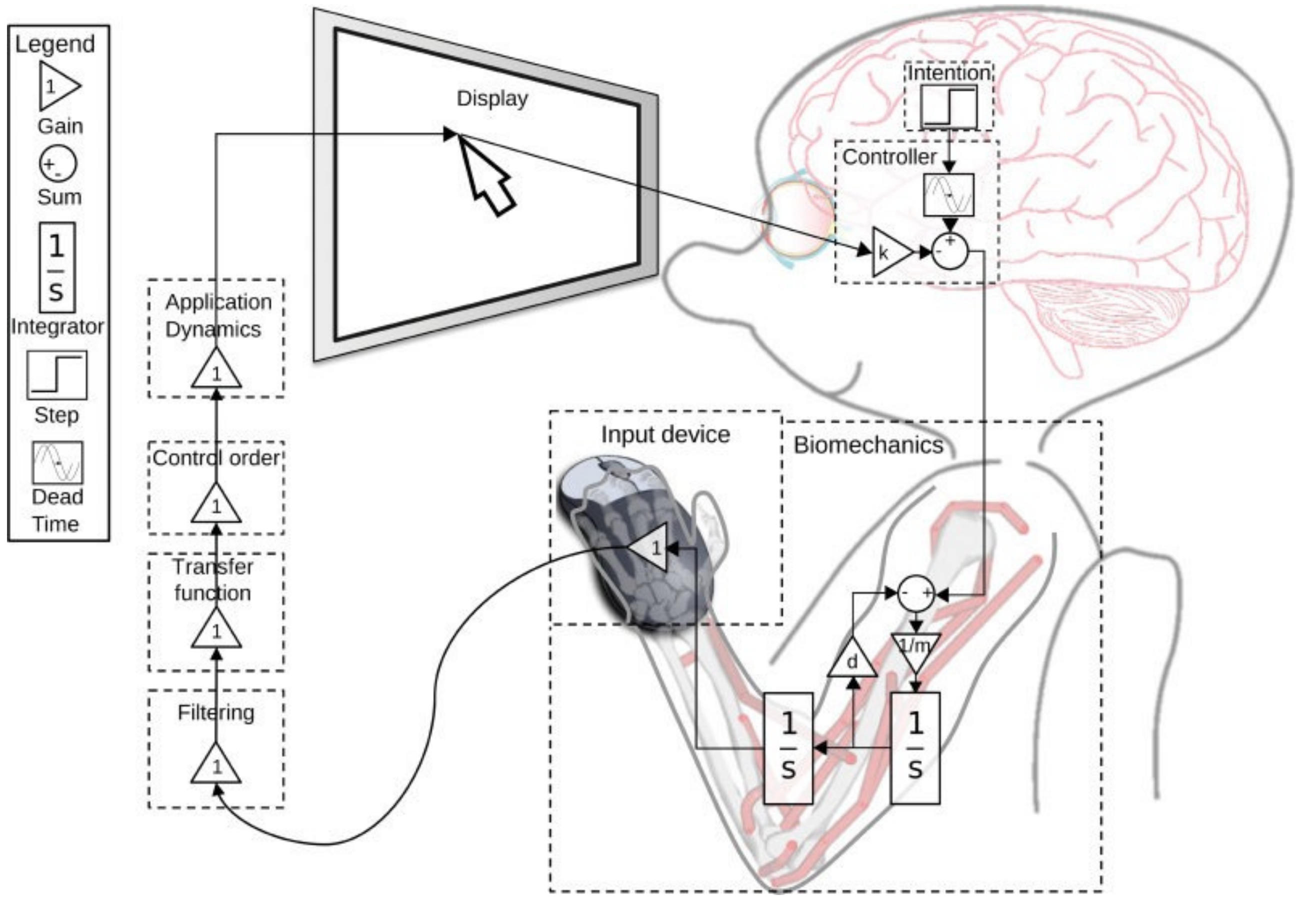
- Computers can change states near instantly
- Humans have perceptual bandwidth limitations that demand time to process sensory feedback, cognitive bandwidth limitations on how to decide to act on stimuli and motor bandwidth limitations on carrying out an action/response
- Humans and computers form coupled dynamic systems that must take these properties into account



Control applications

- Hitting a fixed spatial target with a pointer
- Tracking a moving target with a pointer
- Driving a pointer through a spatial continuum of constraints
- Gestures
- Handwriting
- Panning, zooming and fisheye-style distortions
- Inference of user intent based on detection of controlling behaviour

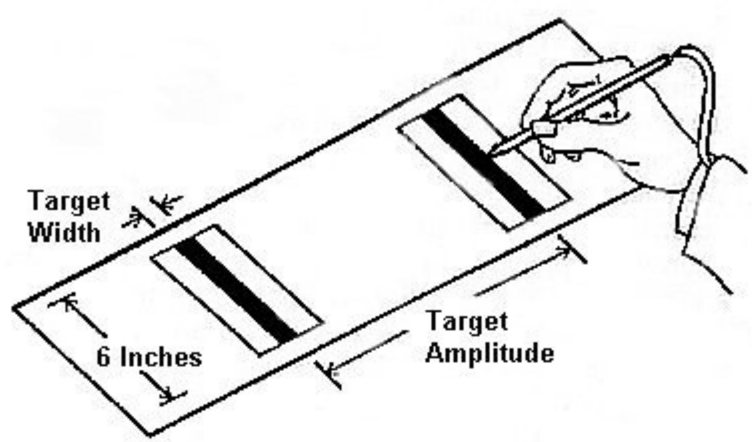
Models of pointing



Jörg Müller, Antti Oulasvirta, and Roderick Murray-Smith. 2017. Control Theoretic Models of Pointing. *ACM Trans. Comput.-Hum. Interact*. 24, 4, Article 27 (August 2017), 36 pages.

A control perspective of Fitts' law

- Recall Fitts' law, which can be formulated as $MT = a + bID$, where:
  - MT is the movement time
  - ID is the index-of-difficulty, $ID = \log_2\left(\frac{2A}{W}\right)$
  - A is the amplitude (distance) to the target
  - W is the width of the target
  - Both a and b are empirically determined parameters



Fitts, P.M. 1954. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology* **47**(6): 381–391.

Fitts' law as first-order lag (Jagacinski and Flach 2003)

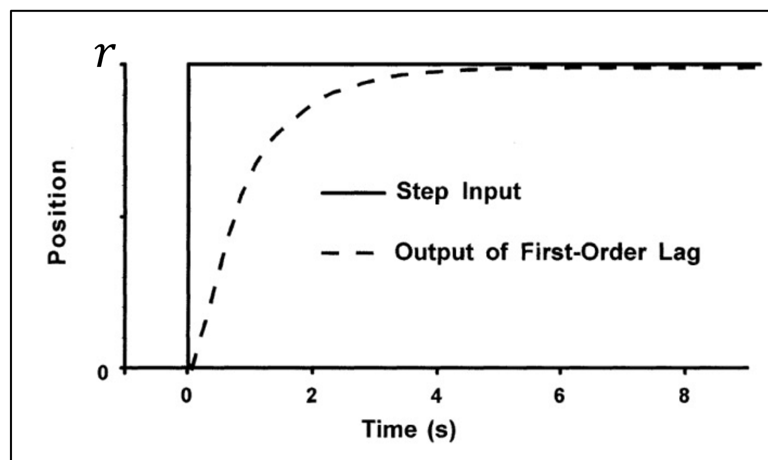
- Proposition: a change in position from the home position to the target is a step change in reference variable r (equivalent to amplitude *A* in Fitts' law)
- Set the controller to a first-order controller with a gain k and integrator $\dot{x} = Bu$, where the control signal $u = r - x$ and $B = k$
- A step change, r from initial state $x = 0$, results in a response of the first order lag which is exponential: $x(t) = r(1 - e^{-kt})$
- For a target of size w (W in Fitts' law) centred on r, the time taken to get within $\frac{1}{2}w$ of r is:

$$x(t) = r\left(1 - e^{-kt}\right) = r - \frac{1}{2}w$$

$$e^{-kt} = \frac{w}{2r}$$

$$-kt = \ln\frac{w}{2r}$$

$$t = \frac{1}{k}\ln\frac{2r}{w}$$



Fitts' law as first-order lag (Jagacinski and Flach 2003)

- Changing to a base 2 logarithm: $t = \frac{\ln 2}{k} \log_2 \frac{2r}{w}$, which is similar to $ID = \log_2\left(\frac{2A}{W}\right)$
- The gain of the forward loop k affects the speed of target acquisition
  - A large k results in a short movement time, and vice versa for a small k
- The time constant for this first-order lag system is $\frac{1}{k}$, the time it takes for the system's response to reach 63% of its steady state value for a step input from zero initial conditions
- The gain of the forward loop k is a measure of the system's sensitivity to error
  - A large k means the system is very sensitive to errors and quick to correct them