Psychophysics
(an introduction)

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Summary

- What is psychophysics?
- The process of measuring
- Classic psychophysics
- Threshold measurement
- Matching
- Examples and advise

Psychophysics

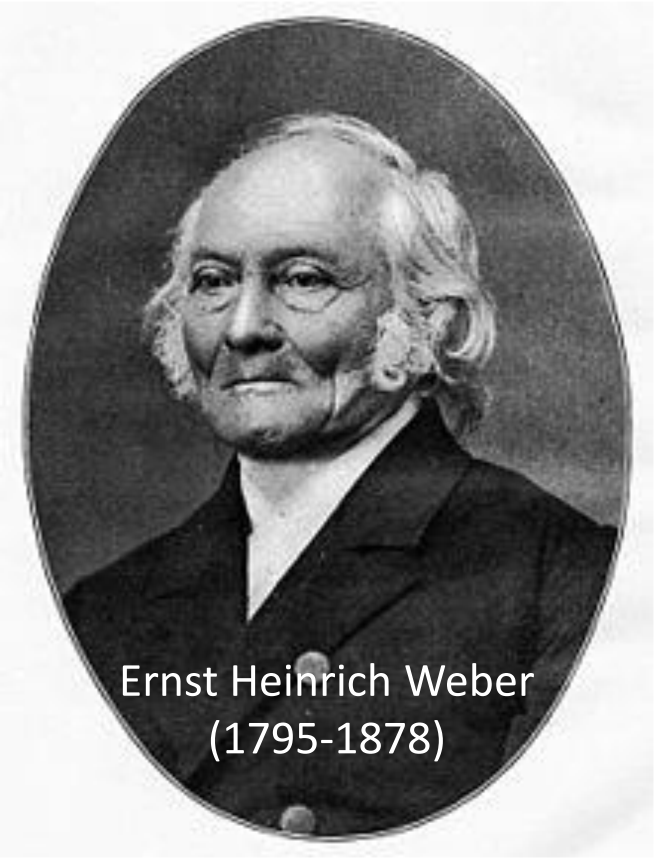
> **Investigates the relationship between physical stimuli and the sensations and perceptions they produce**

Gustav Theodor Fechner (1801 – 1887)

- German experimental psychologist, philosopher, and physicist.
- Early pioneer in Experimental Psychology and founder of Psychophysics.
- Studied medicine in Dresden and from 1818
- Appointed professor of physics at Leipzig in 1834.
- Earned his PhD from Leipzig in 1835.
- *Elemente der Psychophysik* (1860)
- The Weber–Fechner law
- Founder of the field of Experimental Aesthetics
- Developed the notion of the median
- The Fechner colour effect
- Fechner's paradox
- …

Experimental Psychology

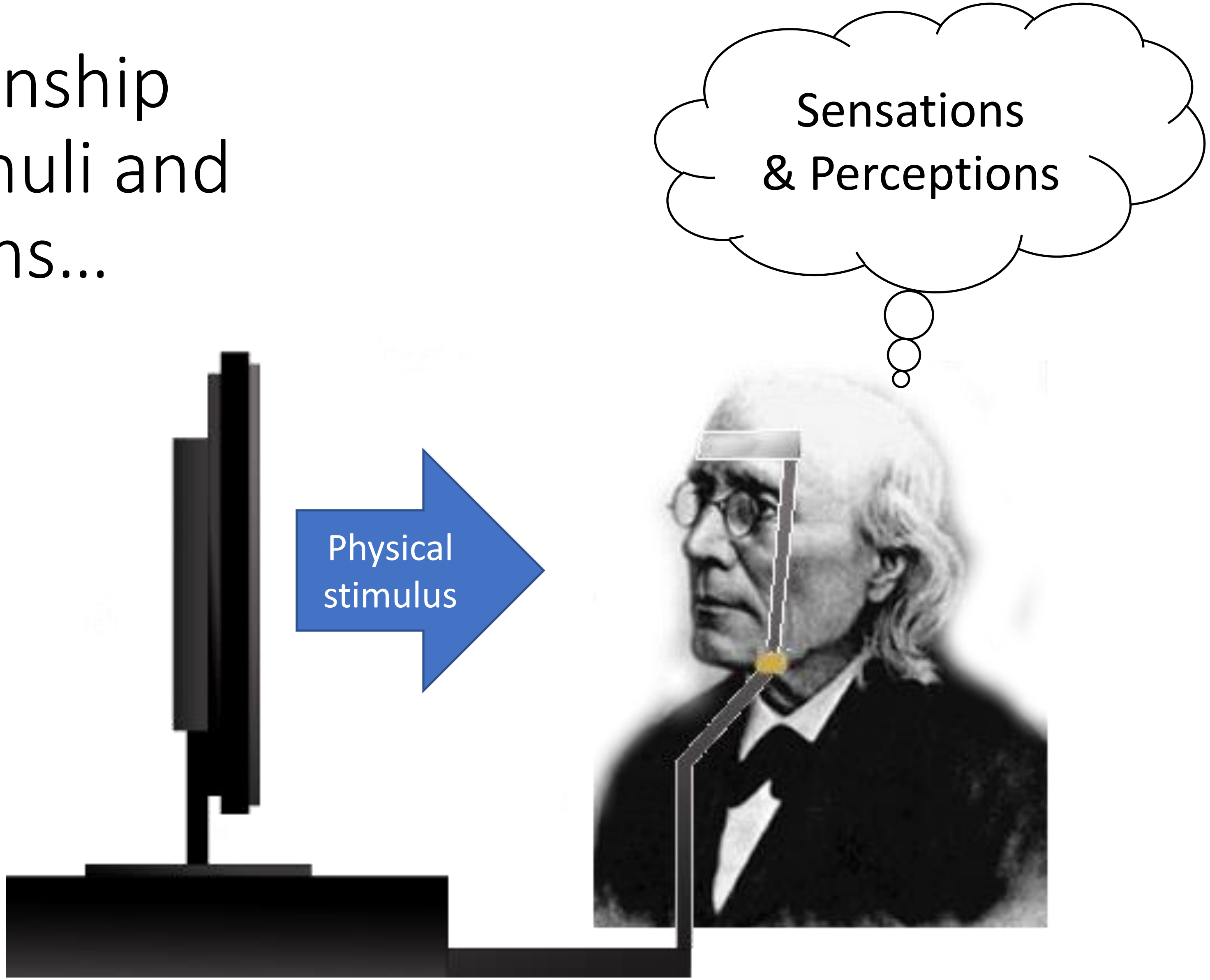
"Applies experimental methods to study psychology and the processes that underlie it."



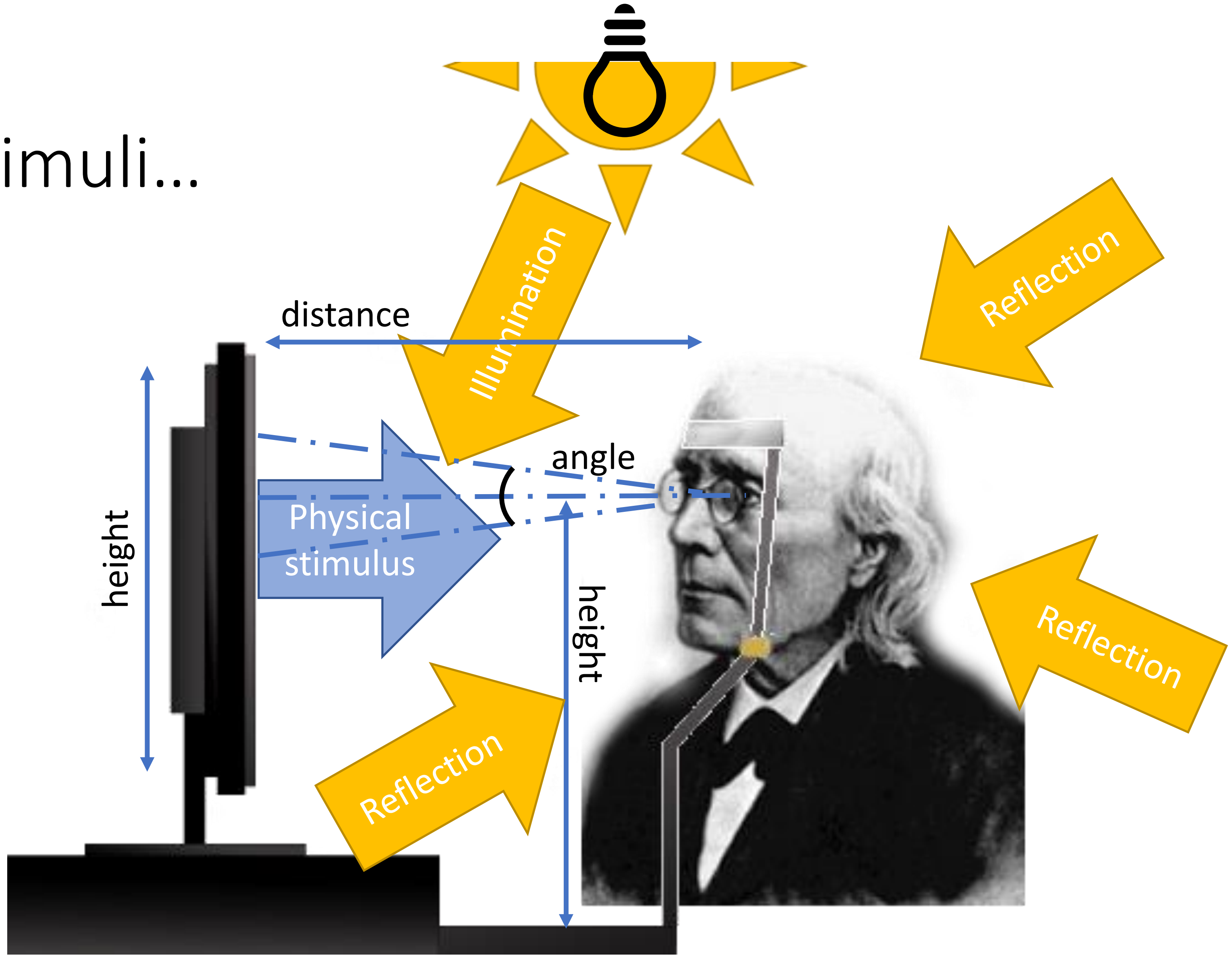
- German physiologist and physician.
- Professor in comparative anatomy at the University of Leipzig (1818)
- One of the founders of Experimental Psychology
- Just-Noticeable Difference
- Weber's Law (later developed into the Weber–Fechner law)
- Experimental Wave Theory
- Hydrodynamics
- Two-point Threshold Technique
- Weber’s Illusion

Psychophysics.

Measuring the relationship between physical stimuli and sensations/perceptions...



Measuring physical stimuli…



The process of measuring physical stimuli

- Experimental error and uncertainty

The **Experimental Error** is the difference between a measured value of a quantity and its true value

…any measured quantity has an associated error.

The process of measuring physical stimuli

The smallest value that our instrument allows us to measure is a millimetre.

The plank of wood in the example measures 194 mm and that I am confident of this value within half a millimetre range

The true value of the length is within the limits: $[x - \Delta x, x + \Delta x]$ where $\Delta x = 0.5$ mm

$$x = 194 \mp 0.5 \text{ mm}$$

The process of measuring physical stimuli

Our experimental error depends on the method of measurement.

Method	Typical error
cheap ruler	0.5 mm
draughtsman's ruler	0.2 mm
callipers with vernier	0.05 mm
travelling microscope	0.005 mm
interferometer	0.00001 mm

Δx Is also called "absolute" error

Absolute error

Two types

- Statistical errors
  - Are random in nature
  - Average behaviour can be predicted
  - Instrument reading errors belong to this class
  - Intrinsically random processes like radioactive decay, etc.
- Systematic errors
  - They are not random
  - Usually arise from problems in the design of the experiment
  - Affect all measurements in some well-defined way
  - They are nasty

Absolute error

Common solutions

- Statistical error
  - Average them out
  - Buy better instruments (instrument reading errors)
  - Be more careful when measuring
- Systematic errors
  - Easy to correct but difficult to recognize… (ouch!)
  - Look for anomalies in the data
  - Nonzero values where zero is expected
  - Inability to reproduce results, etc.

Accuracy and Precision

- **Accuracy** refers to the confidence limits: $[x - \Delta x, x + \Delta x]$

- **Precision** refers to the measure's reproducibility

Accuracy and Precision

- **Accuracy** refers to the confidence limits: $[x - \Delta x, x + \Delta x]$

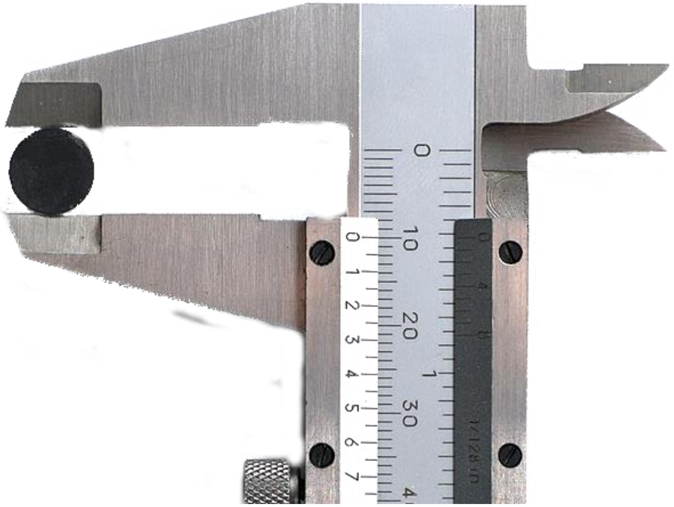
- **Precision** refers to the measure's reproducibility

Accuracy and Precision

High accuracy

1/10 mm ruler spacing: $\Delta x = 0.05\text{mm}$

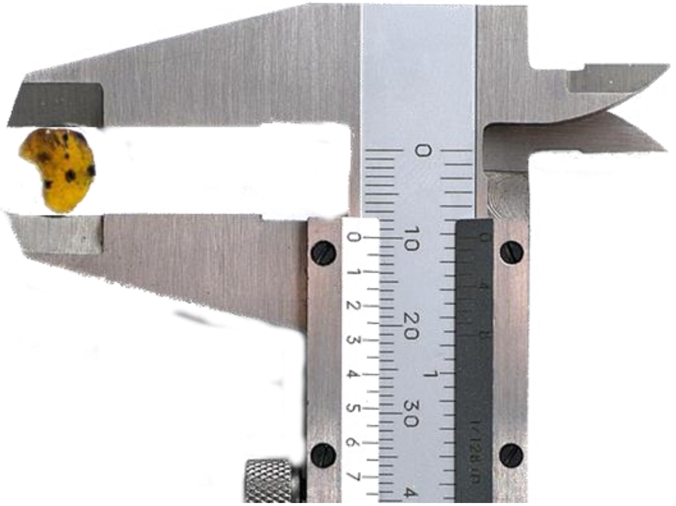
- 100.1 mm
- 100.2 mm
- 100.0 mm
- 100.1 mm
- 100.1 mm



Low precision

(High variability)

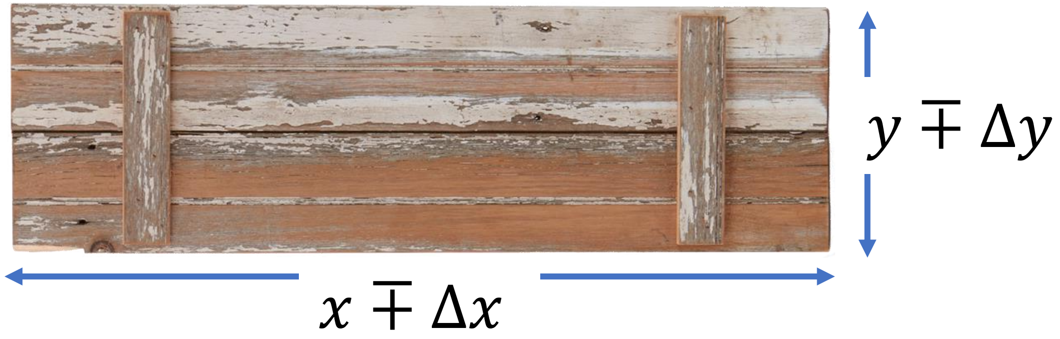
- 98.3 mm
- 75.4 mm
- 102.6 mm
- 99.7 mm
- 103.4 mm



Error propagation

Errors propagate through mathematical formulae

Example:



Perimeter:

$$P = 2x + 2y$$

$$\Delta P = \Delta x + \Delta y$$

Surface:

$$S = x \cdot y$$

$$\frac{\Delta S}{S} = \frac{\Delta x}{x} + \frac{\Delta y}{y}$$

"Relative" error

Error propagation

General case:

Suppose we already measured $X \mp \Delta X$ where x belongs to some function $f(x)$ and $F = f(X)$

We can evaluate $f(X + \Delta X)$ and $f(X - \Delta X)$ to get $F \mp \Delta F$

But… we can write:

$$\frac{\mathrm{d}f}{\mathrm{d}x}(x = X) = \lim_{\Delta x \to 0} \frac{\Delta F}{\Delta X}$$

Since Δ*x* is small:

$$\Delta F = \left| \frac{df}{dx} \right| \Delta X$$

Psychophysical Threshold measurement

- Absolute threshold

- Difference threshold

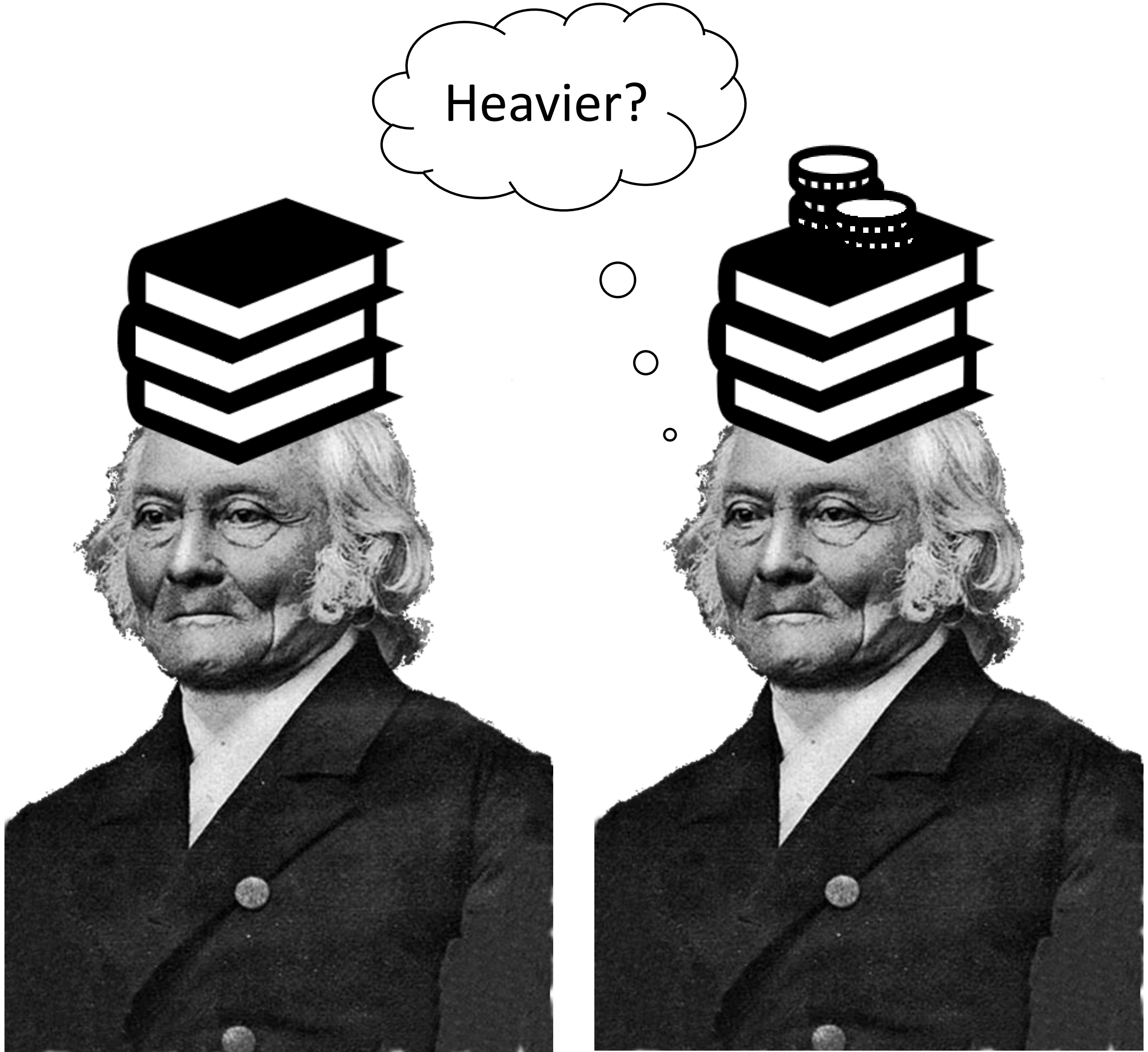
Psychophysical Threshold measurement

- **Absolute threshold**

  The minimum amount of stimulus energy necessary to elicit a sensation.

Psychophysical Threshold measurement

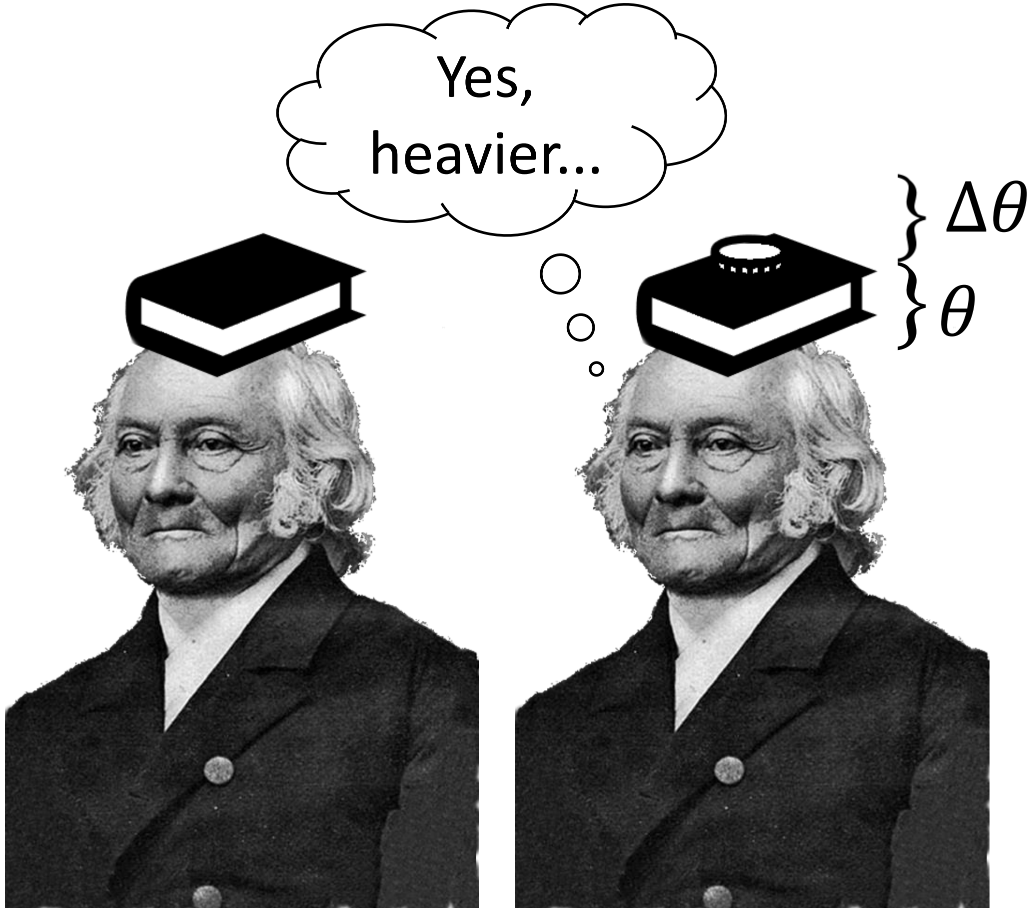
- Absolute threshold

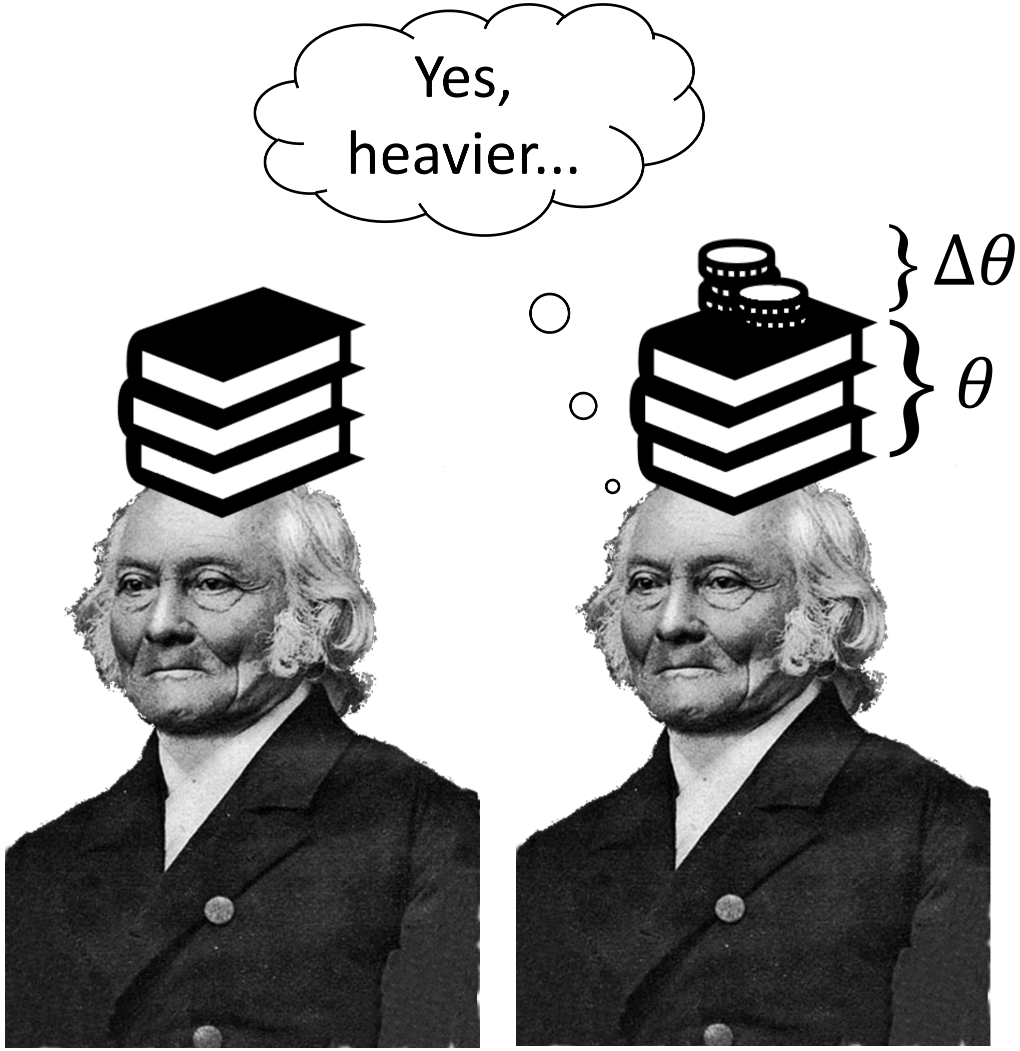


- **Difference threshold**

The amount of change in the stimulus necessary to elicit a *just noticeable* increment in the sensation (**just noticeable difference or *jnd***)

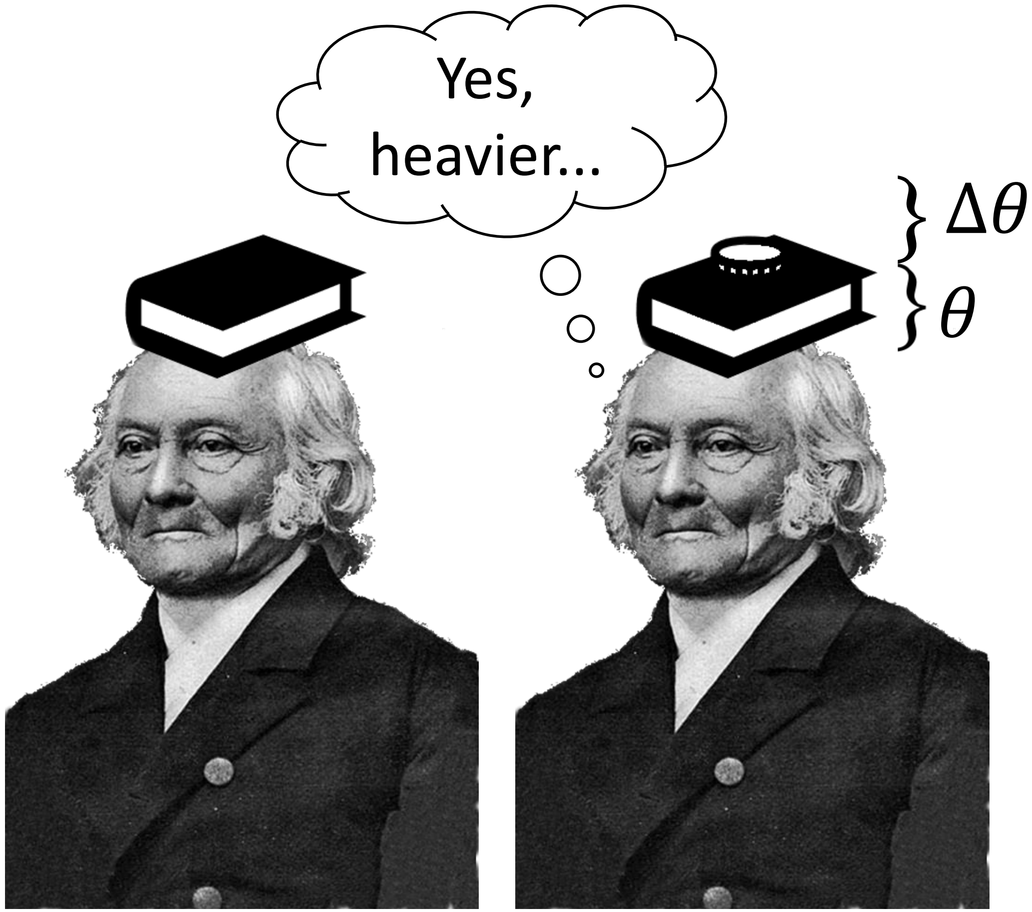
Weber’s law

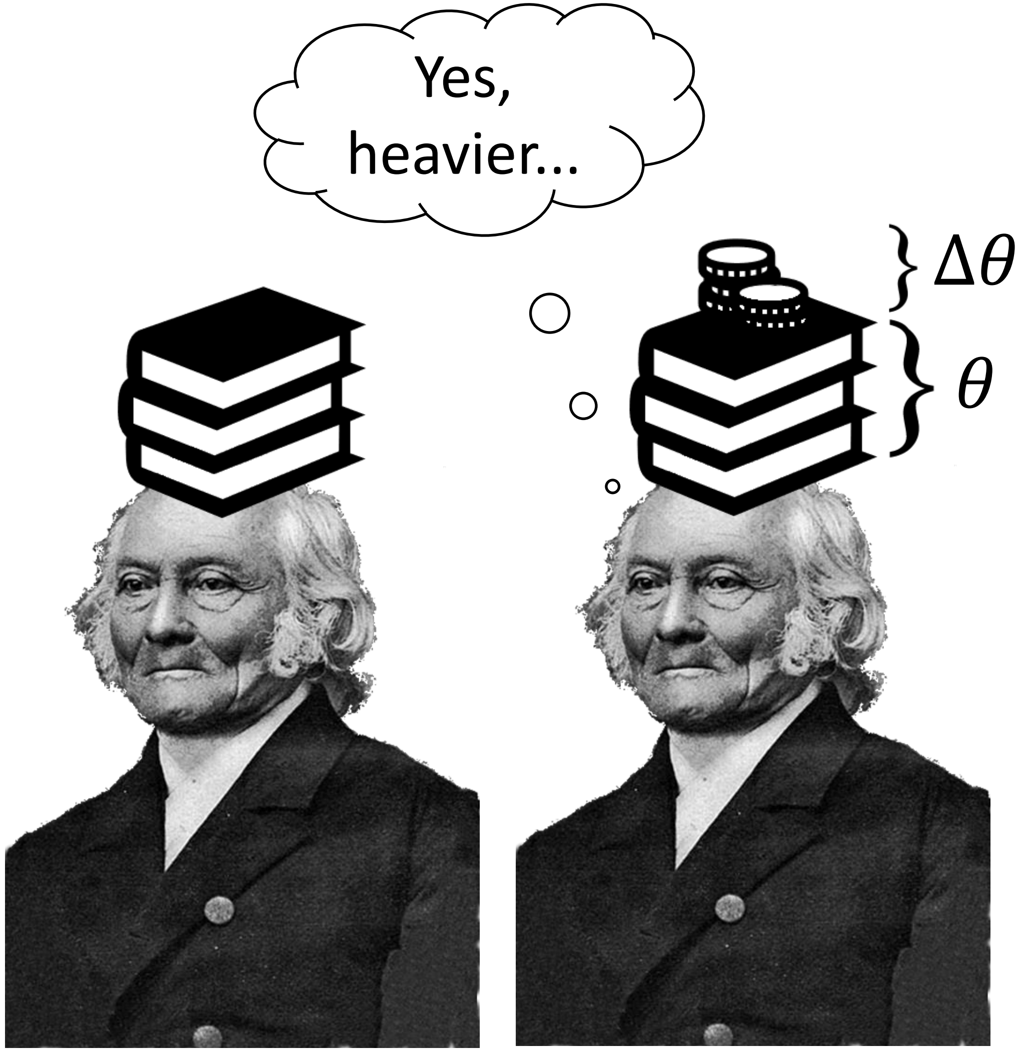

Yes,
heavier...
$\Delta\theta$
θ


Yes,
heavier...
$\Delta\theta$
θ

Weber's law

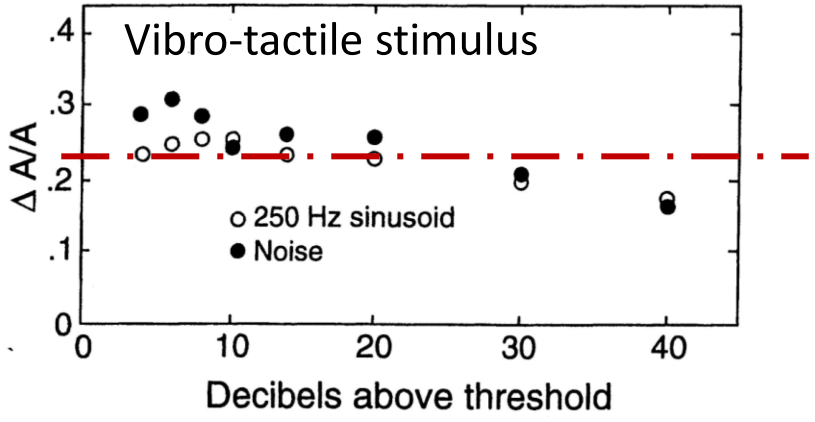
$$\frac{\Delta\theta}{\theta} = c$$



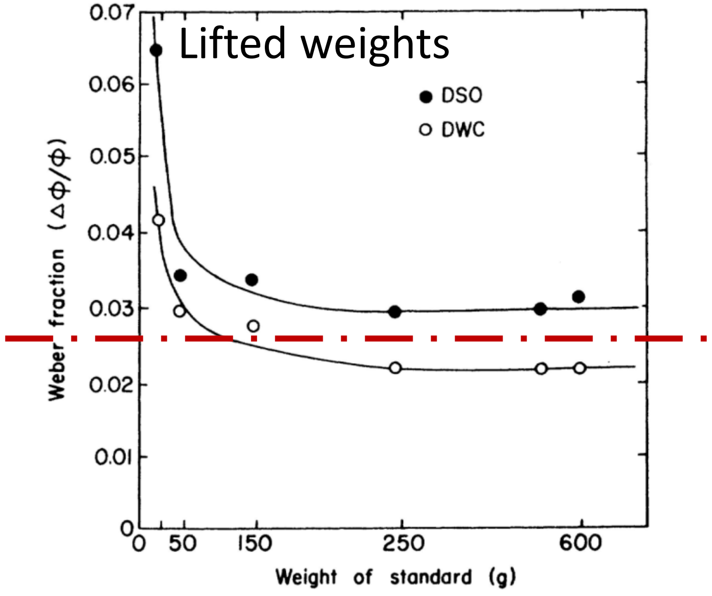


Weber's law

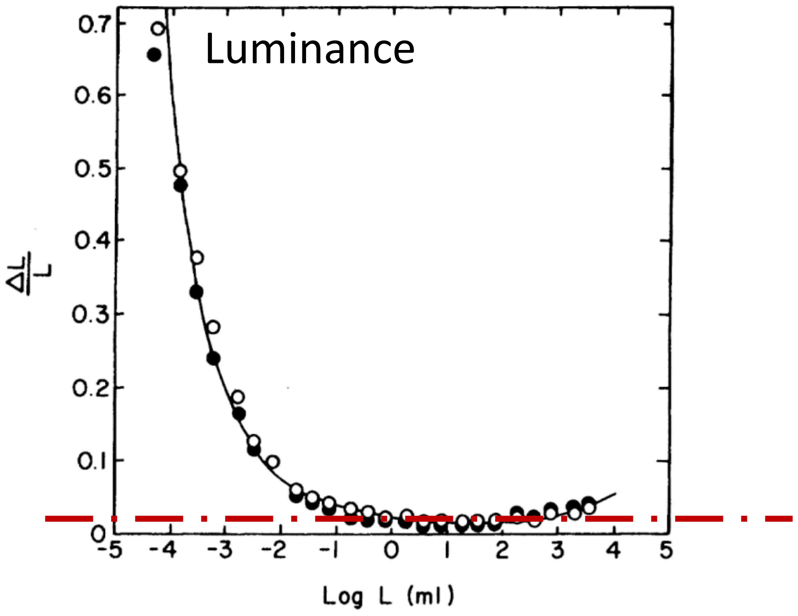
$$\frac{\Delta\theta}{\theta} = c$$



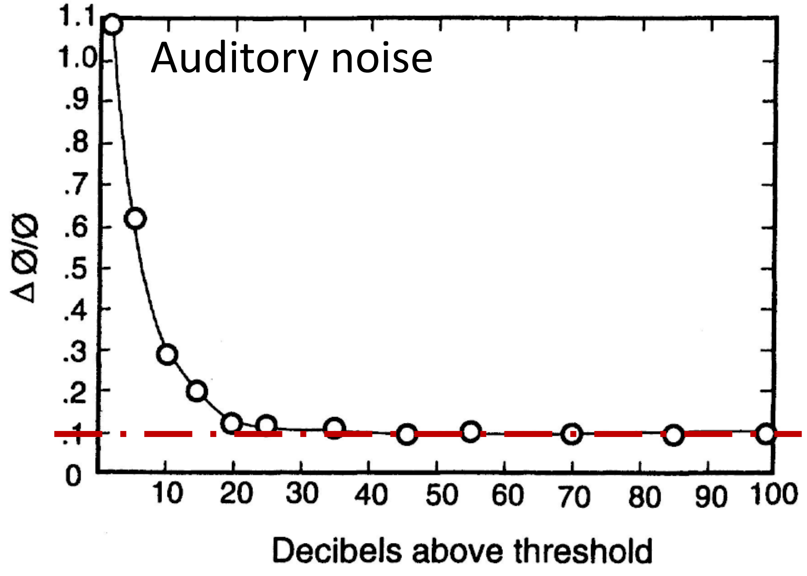
Riesz (1928)



Engen (1971), two observers



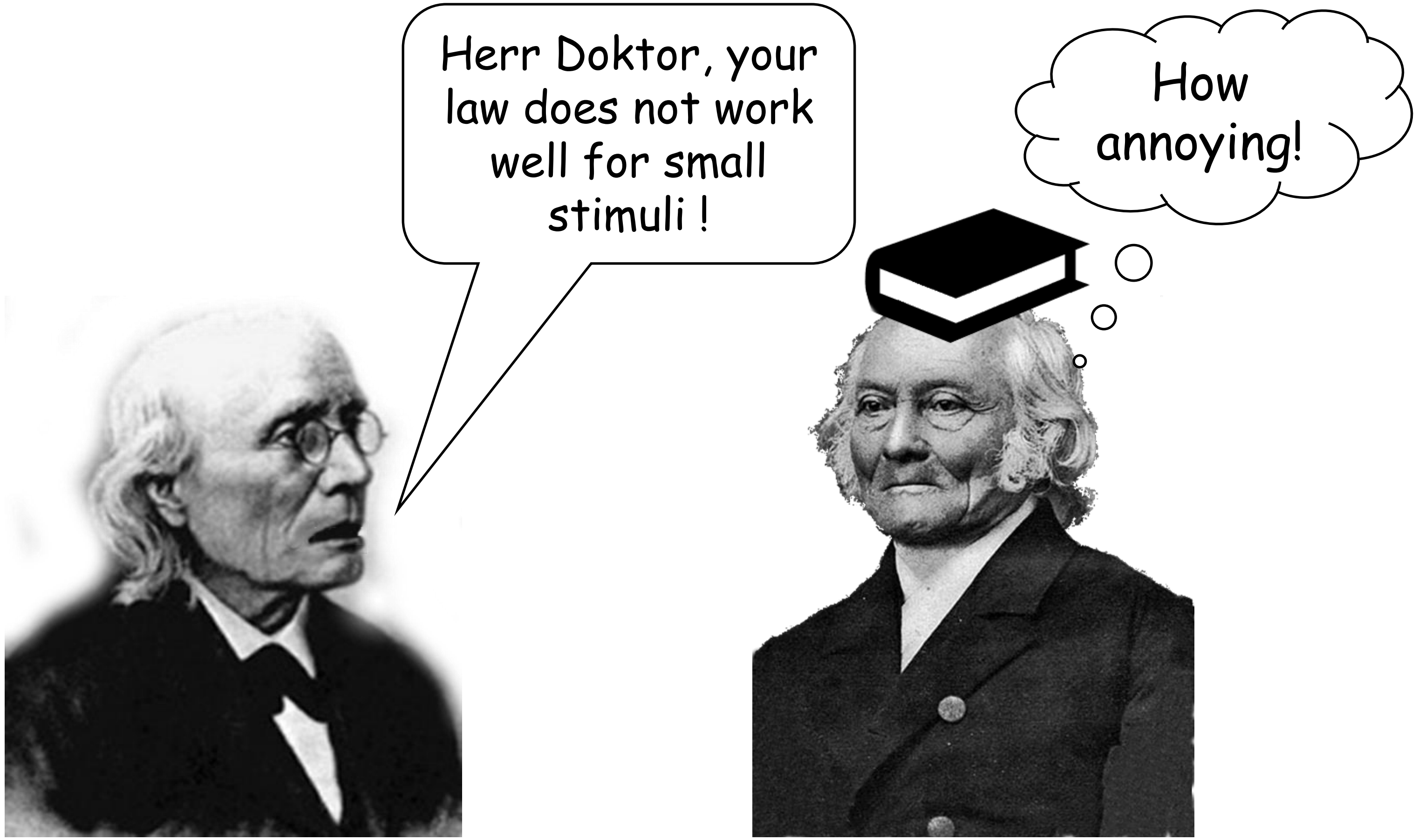
König and Boldhun (1889)

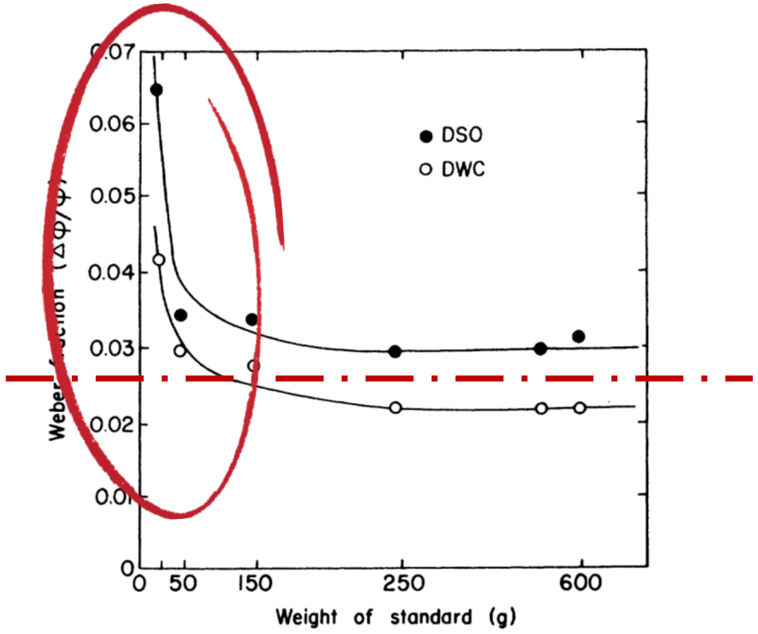


Miller (1947)

Weber's law

$$c = \frac{\Delta\theta}{\theta}$$





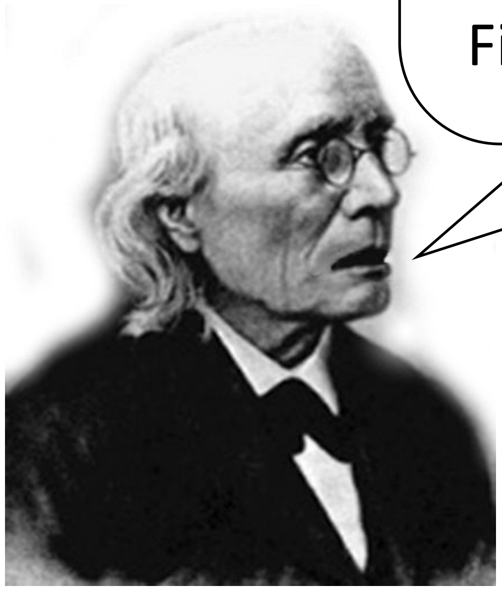
Weber's law

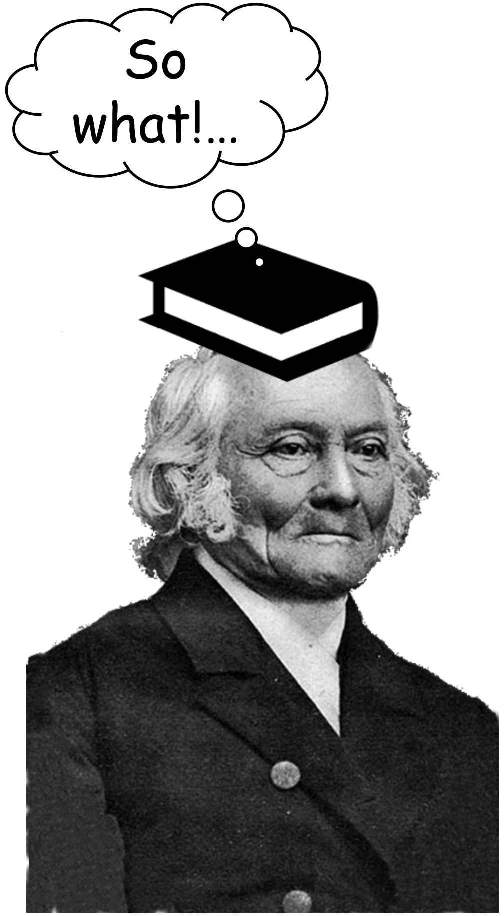
$$c = \frac{\Delta\theta}{\theta}$$

$$c = \frac{\Delta\theta}{\theta + a}$$

where a = background noise of the nervous system

Fits the data much better!





Weber's law $c = \frac{\Delta\theta}{\theta}$

In fact, I can derive a much better expression for your law considering *c* as the **magnitude of the sensation** experienced (Ψ)...

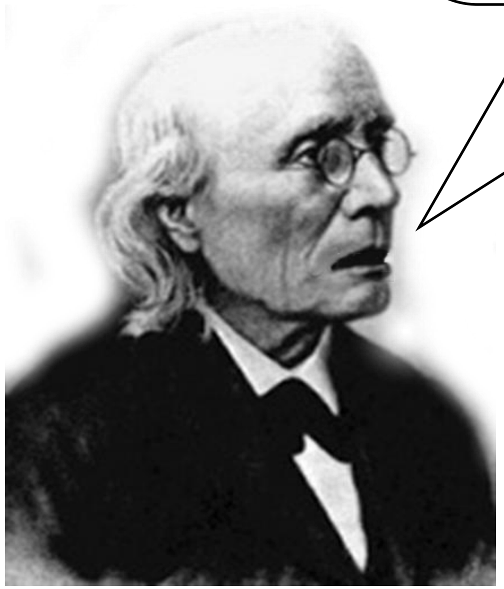
$$d\Psi = k\frac{d\theta}{\theta}$$

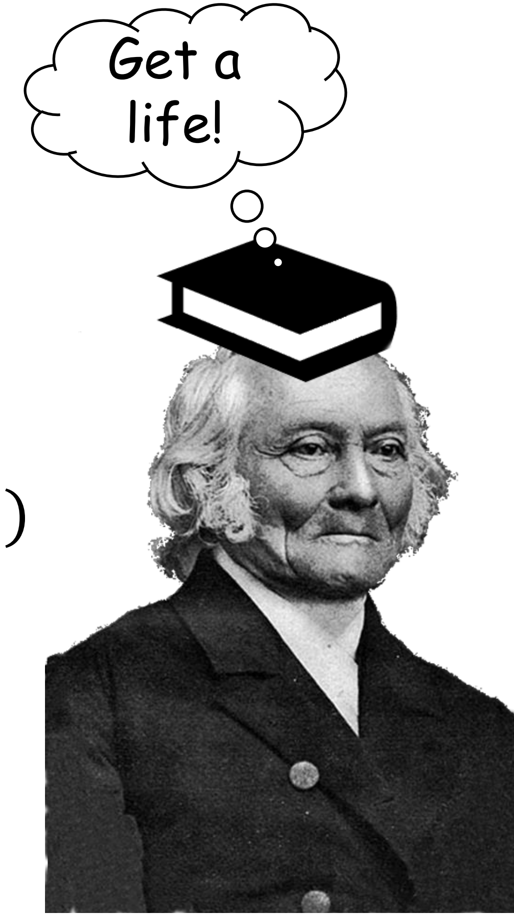
$$\int d\Psi = k\int\frac{d\theta}{\theta}$$

$$\Psi = k \cdot \ln(\theta) + C$$

$$\Psi = k \cdot \ln(\theta) - k \cdot \ln(\theta_0)$$

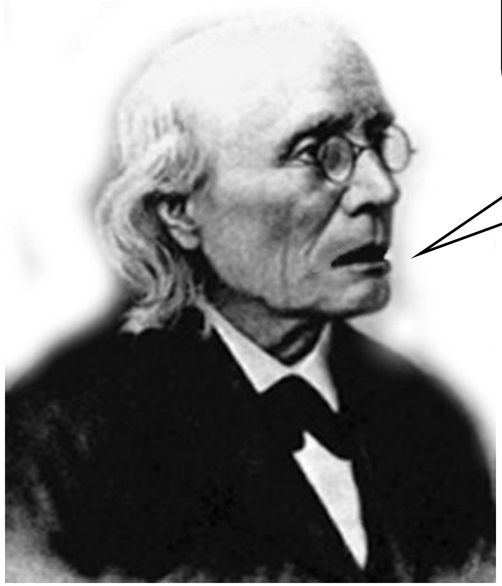
$$\Psi = k \cdot \ln\left(\frac{\theta}{\theta_0}\right)$$





~~Weber's law~~

Fechner's law



…and *k* depends of the sensory modality considered…

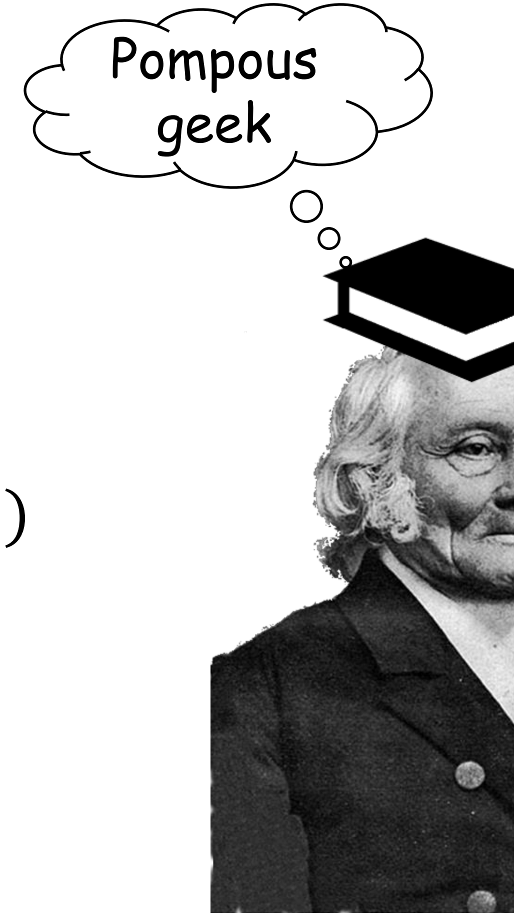
$$d\Psi = k\frac{d\theta}{\theta}$$

$$\int d\Psi = k\int\frac{d\theta}{\theta}$$

$$\Psi = k\cdot\ln(\theta) + \mathrm{C}$$

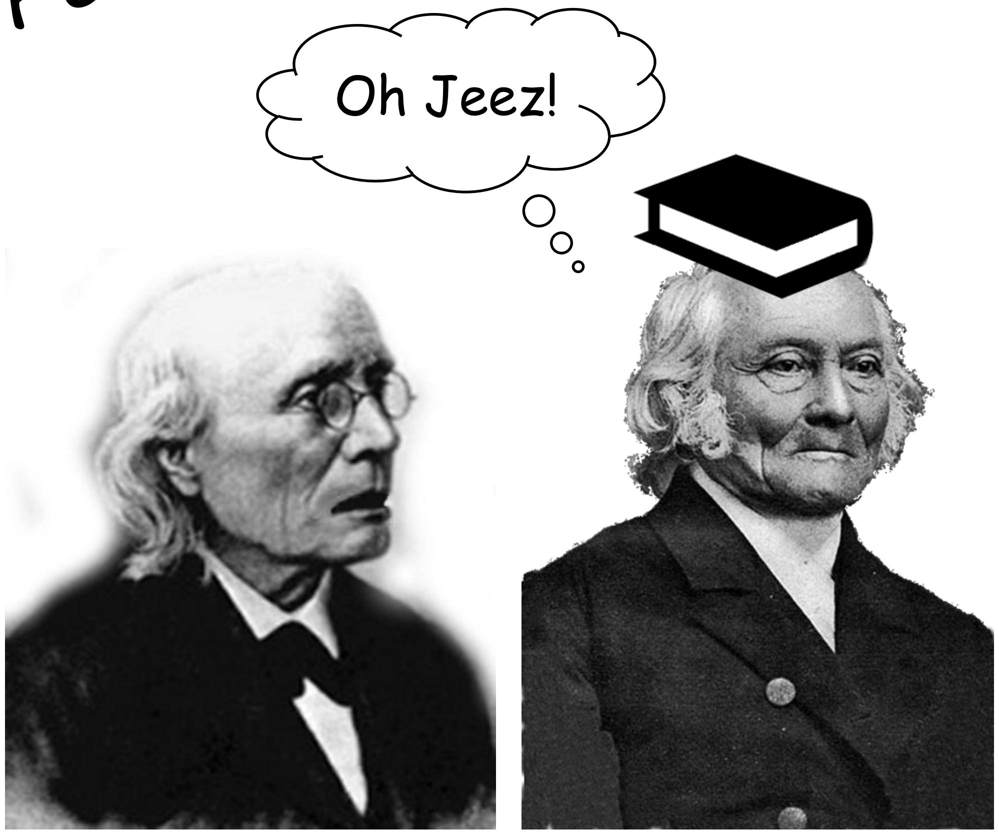
$$\Psi = k\cdot\ln(\theta) - \mathrm{k}\cdot\ln(\theta_0)$$

$$\Psi = k\cdot\ln\left(\frac{\theta}{\theta_0}\right)$$

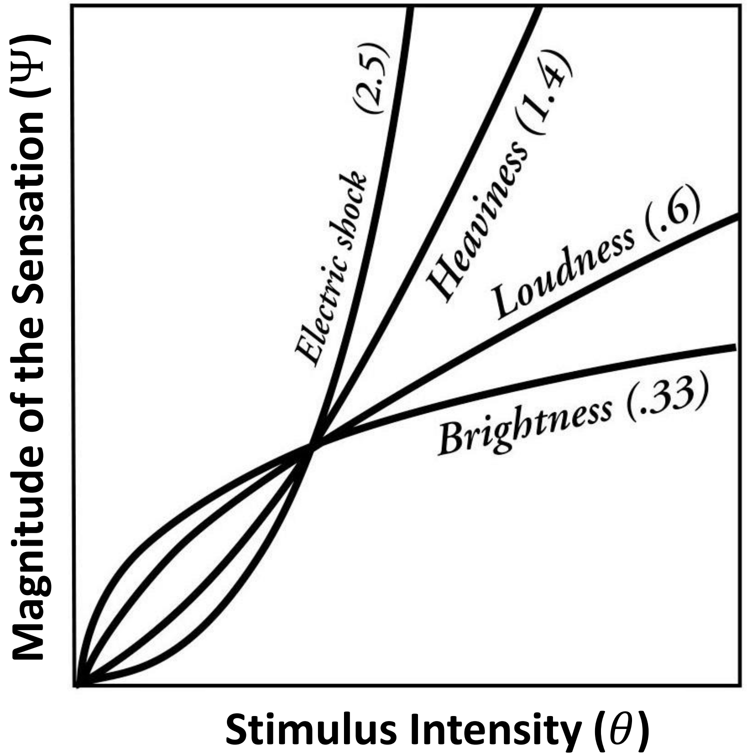


~~Weber’s law~~

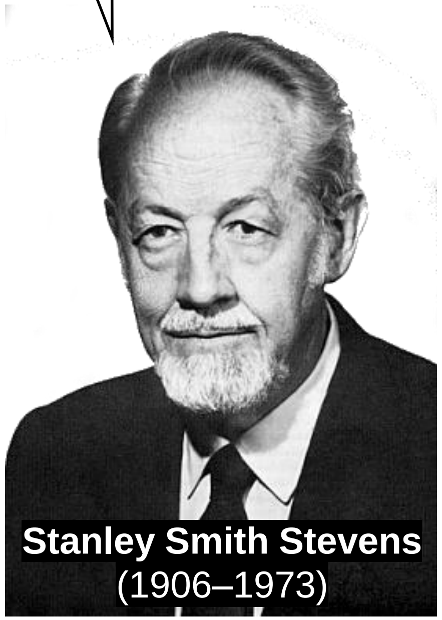
Fechner’s law



$$\Psi = k \cdot \theta^{a}$$



In fact you guys are both wrong...



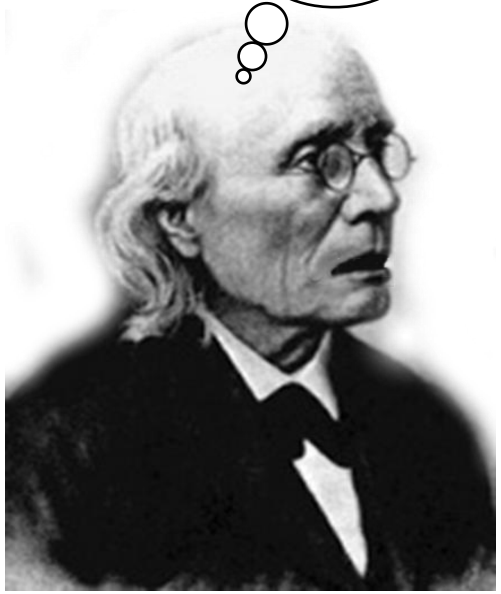
~~Weber's law~~

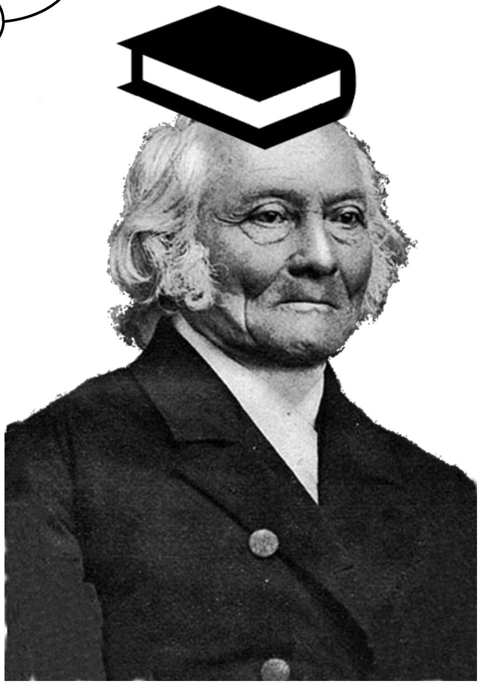
$$\Psi = k \cdot \theta^{a}$$

~~Fechner's law~~

Stevens' power law

Bloody Americans… not again!





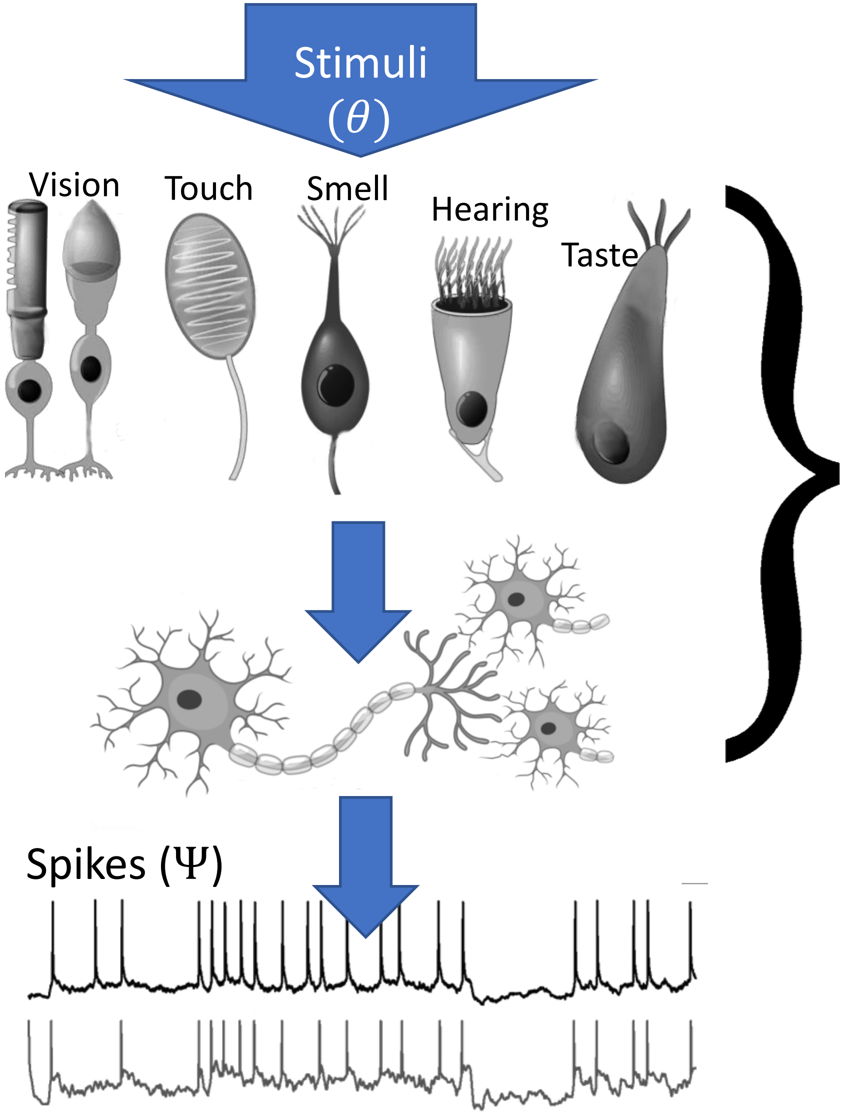
Modality	a	Condition
Loudness	0.67	Sound pressure of 3000 Hz tone
Vibration	0.95	Amplitude of 60 Hz on finger
Vibration	0.6	Amplitude of 250 Hz on finger
Brightness	0.33	5° target in dark
Brightness	0.5	Point source
Brightness	0.5	Brief flash
Brightness	1	Point source briefly flashed
Lightness	1.2	Reflectance of gray papers
Visual length	1	Projected line
Visual area	0.7	Projected square
Redness (saturation)	1.7	Red–gray mixture
Taste	1.3	Sucrose
Taste	1.4	Salt
Taste	0.8	Saccharin
Smell	0.6	Heptane
Cold	1	Metal contact on arm
Warmth	1.6	Metal contact on arm
Warmth	1.3	Irradiation of skin, small area
Warmth	0.7	Irradiation of skin, large area
Discomfort, cold	1.7	Whole-body irradiation
Discomfort, warm	0.7	Whole-body irradiation
Thermal pain	1	Radiant heat on skin
Tactual roughness	1.5	Rubbing emery cloths
Tactual hardness	0.8	Squeezing rubber
Finger span	1.3	Thickness of blocks
Pressure on palm	1.1	Static force on skin
Muscle force	1.7	Static contractions
Heaviness	1.45	Lifted weights
Viscosity	0.42	Stirring silicone fluids
Electric shock	3.5	Current through fingers
Vocal effort	1.1	Vocal sound pressure
Angular acceleration	1.4	5 s rotation
Duration	1.1	White-noise stimuli

List of exponents reported by Stevens

My law can explain much more stuff… ha ha!

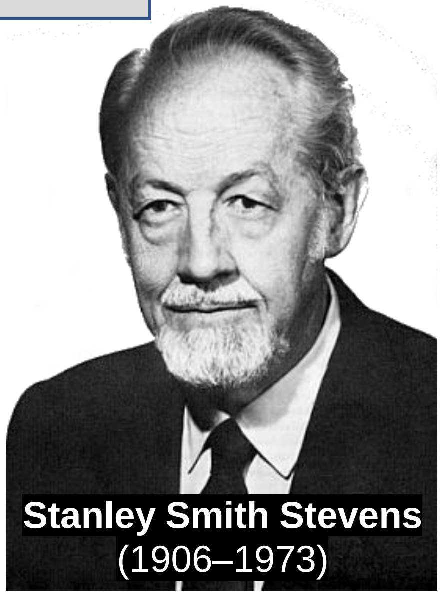
Stanley Smith Stevens
(1906–1973)

Just a transduction process...?



Transduction function

$$\Psi = k \cdot \theta^a$$



Classic psychophysics

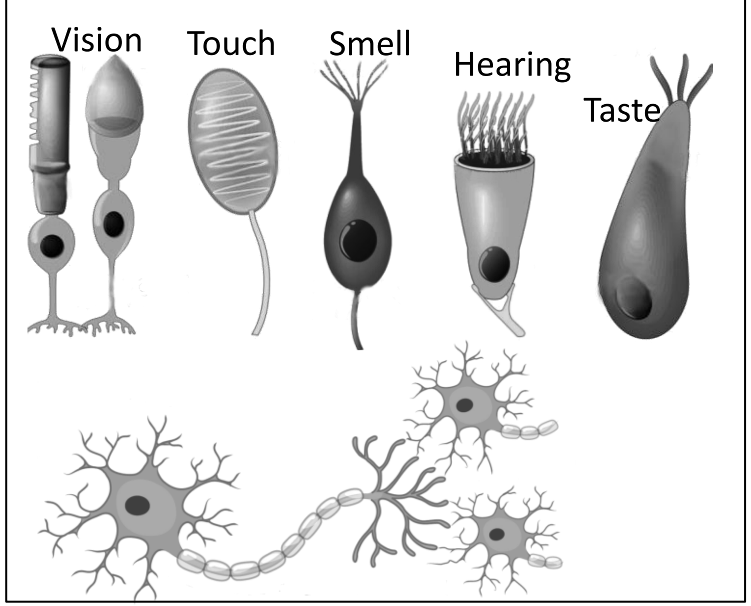
Principle of Nomination:

“There is biunivocal correspondence between the neural activity generated by a stimulus and its perception”

Stimulus A

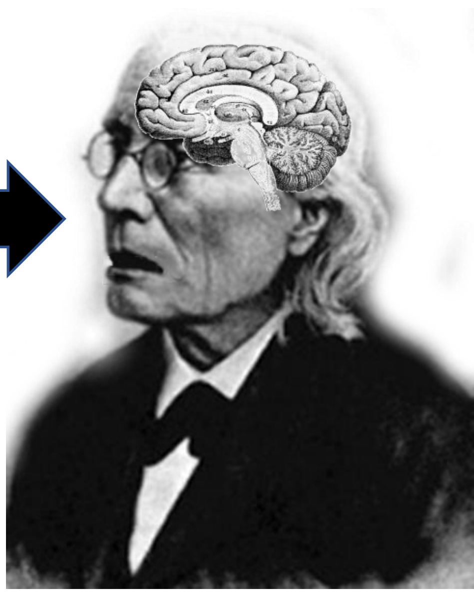
Stimulus B

Transduction



Same neural activity

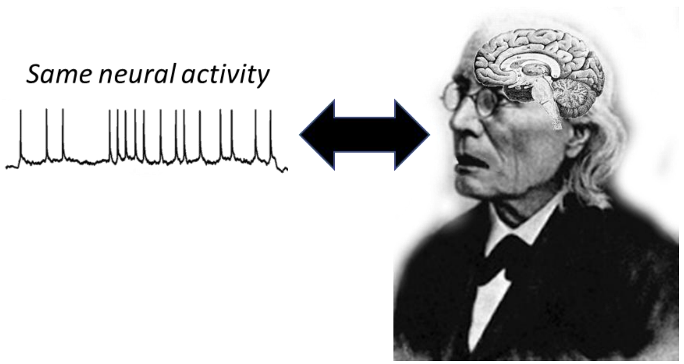
Same perception



Classic psychophysics

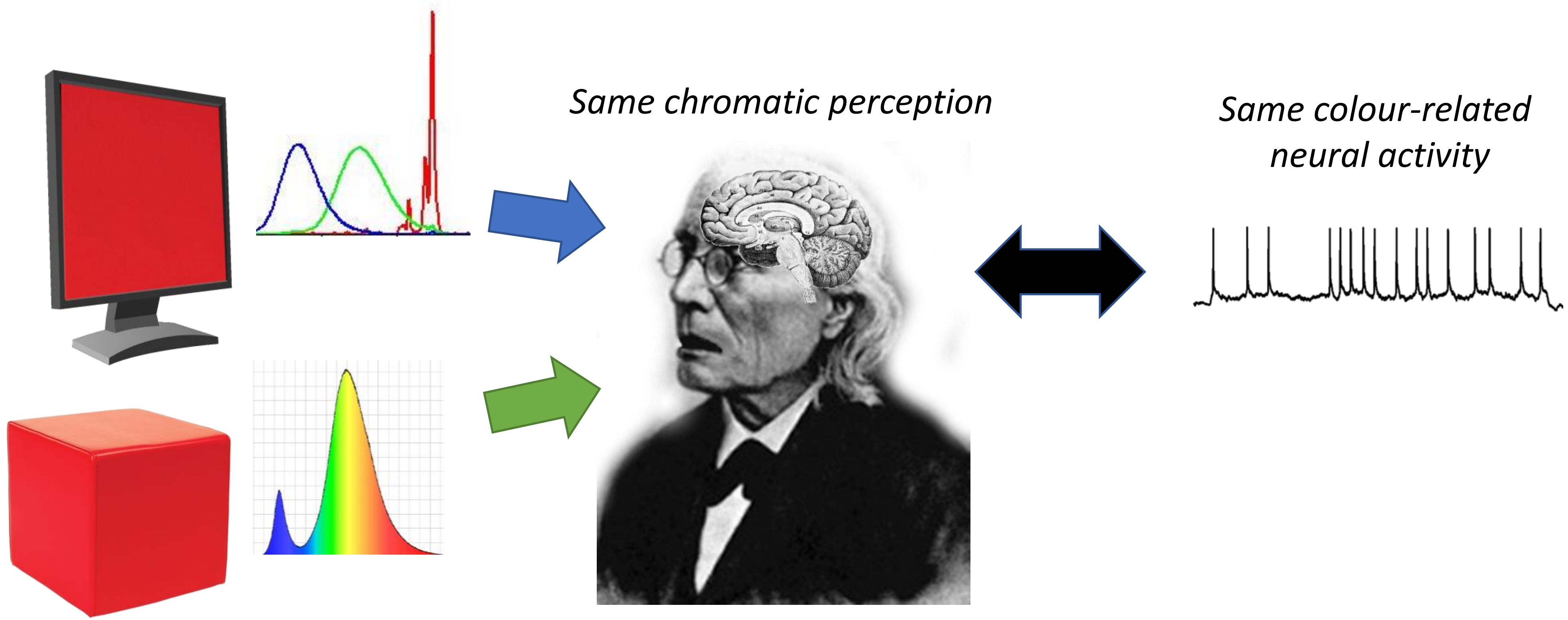
Principle of Nomination:

- Links physics to neural response and sensation
- Allows to use combinations of stimuli that elicit identical responses.
- Allows us to combine findings from different disciplines



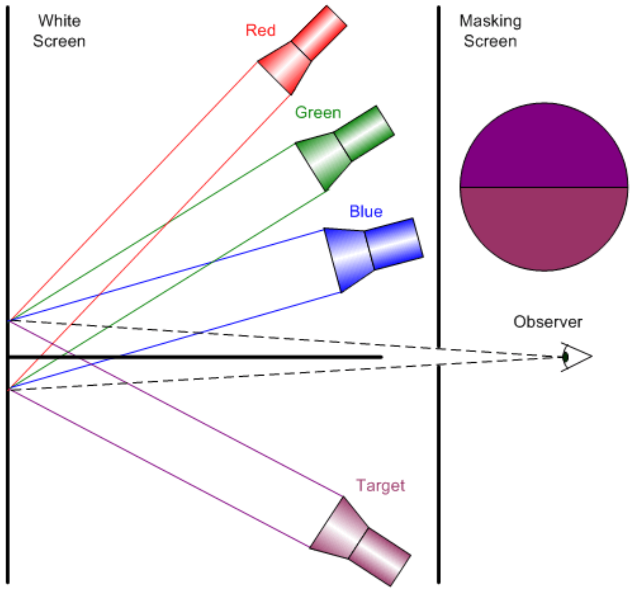
Principle of nomination

The *principle of nomination* allows us to match two different stimuli (e.g. colour matching experiments)…

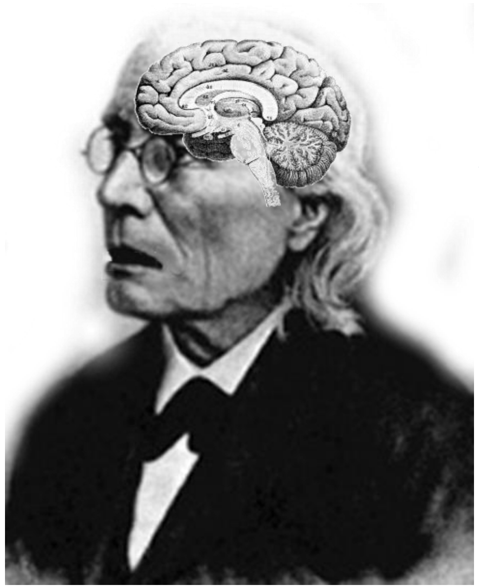


Principle of nomination

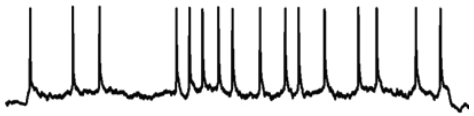
…or to match one property of a stimulus (while keeping other properties the same)…



Same brightness perception



Same brightness-related neural activity



Threshold measurement

- Method of constant stimuli
- Method of limits
- Method of adjustments

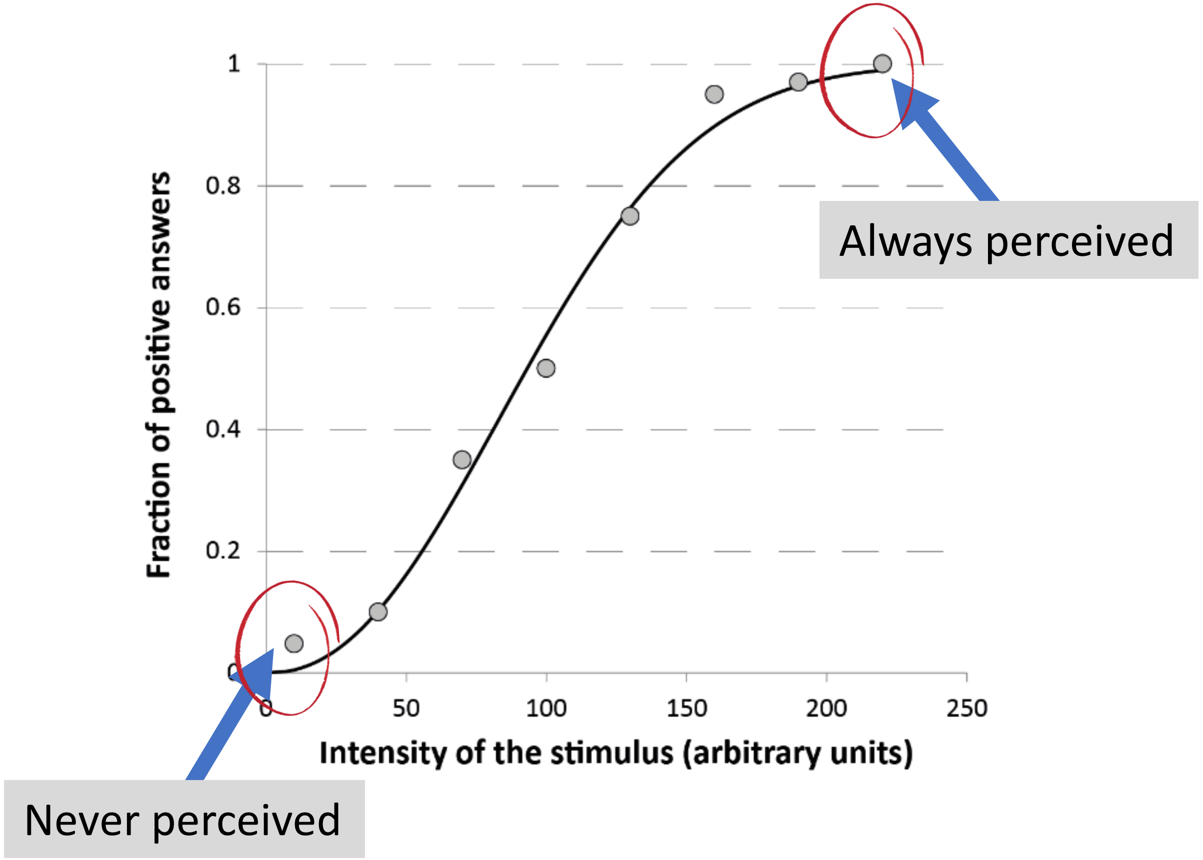
Method of constant stimuli

- The stimuli are fixed beforehand (constant)
- Ranges from “easily detectable” to “almost impossible to detect”
- Intensity should be separated by equal steps

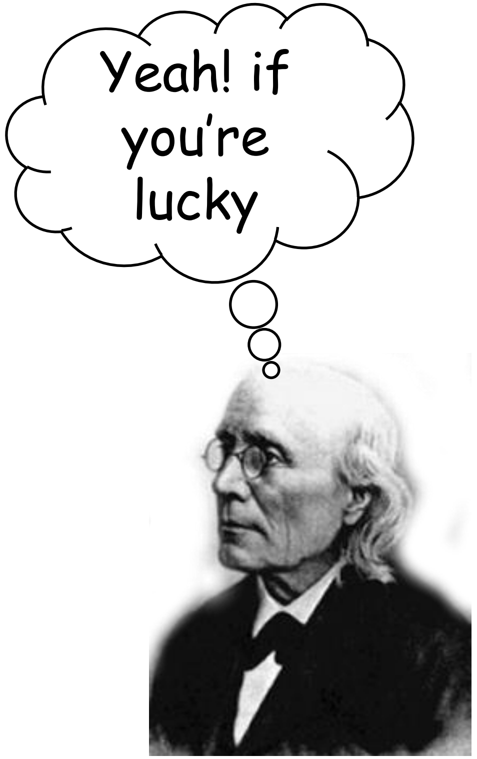
Recipe:

- Present the stimuli in random order (several times)
- Ask “do you perceive the stimulus?”
- Note the fraction of positive answers

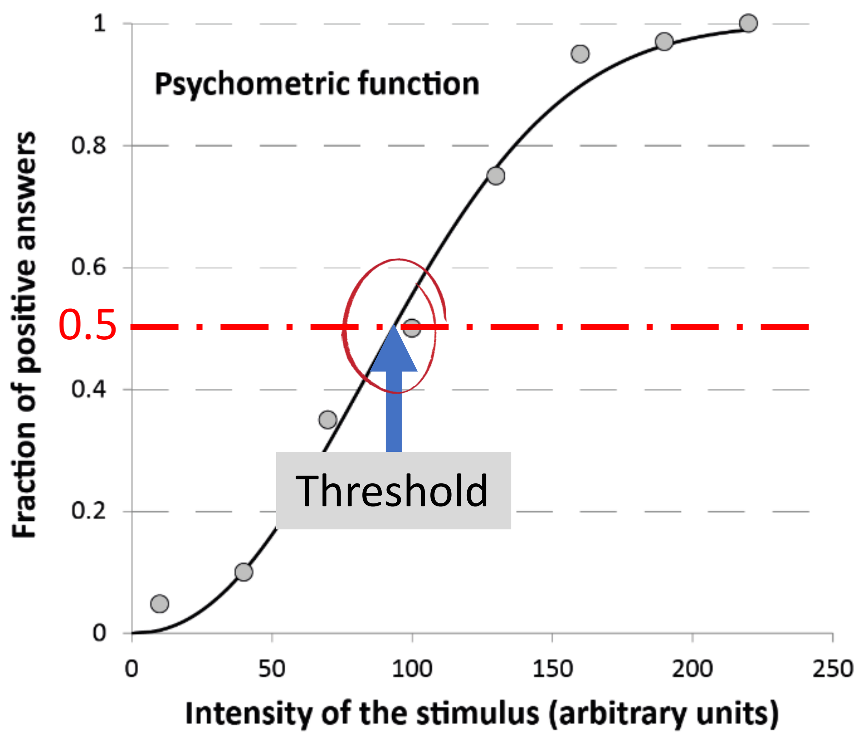
Method of constant stimuli



- Your results should end up looking like this…

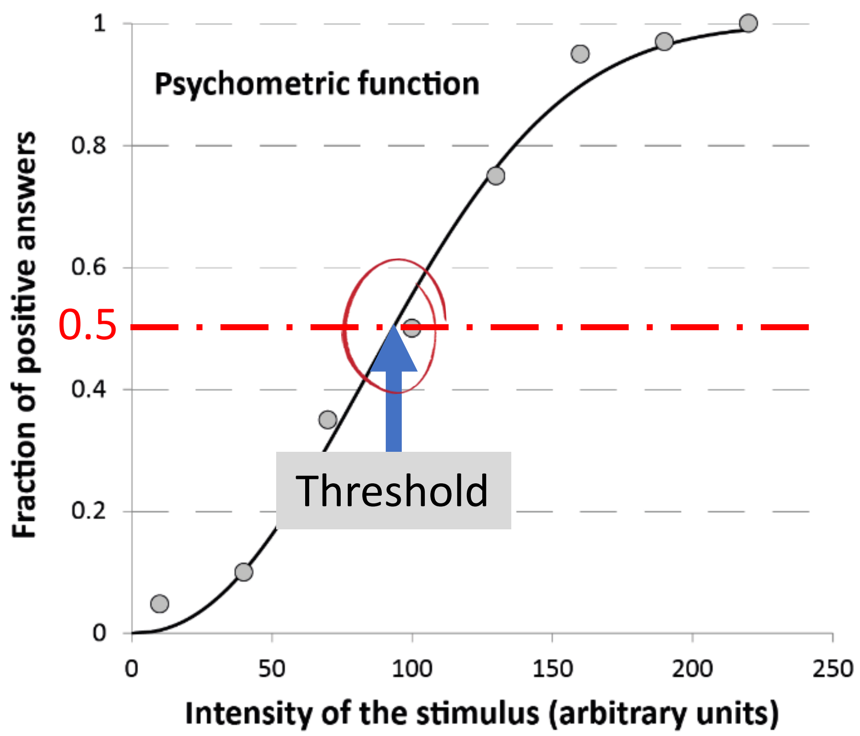


Method of constant stimuli



- Each dot is the average of *n* trials (typically 10)
- Results tend to have a typical sigmoidal shape called **psychometric function**
- Best fit by an *ogive* function which represents the area below a normal distribution curve
- The threshold is the point when the subject perceives the stimulus half the time

Method of constant stimuli



Disadvantages

- Can take really a long time
- Subject boredom
- Subject pressing wrong keys (the ogive can be modified to account for this)
- Subject training recommended
- Pilot trials strongly recommended

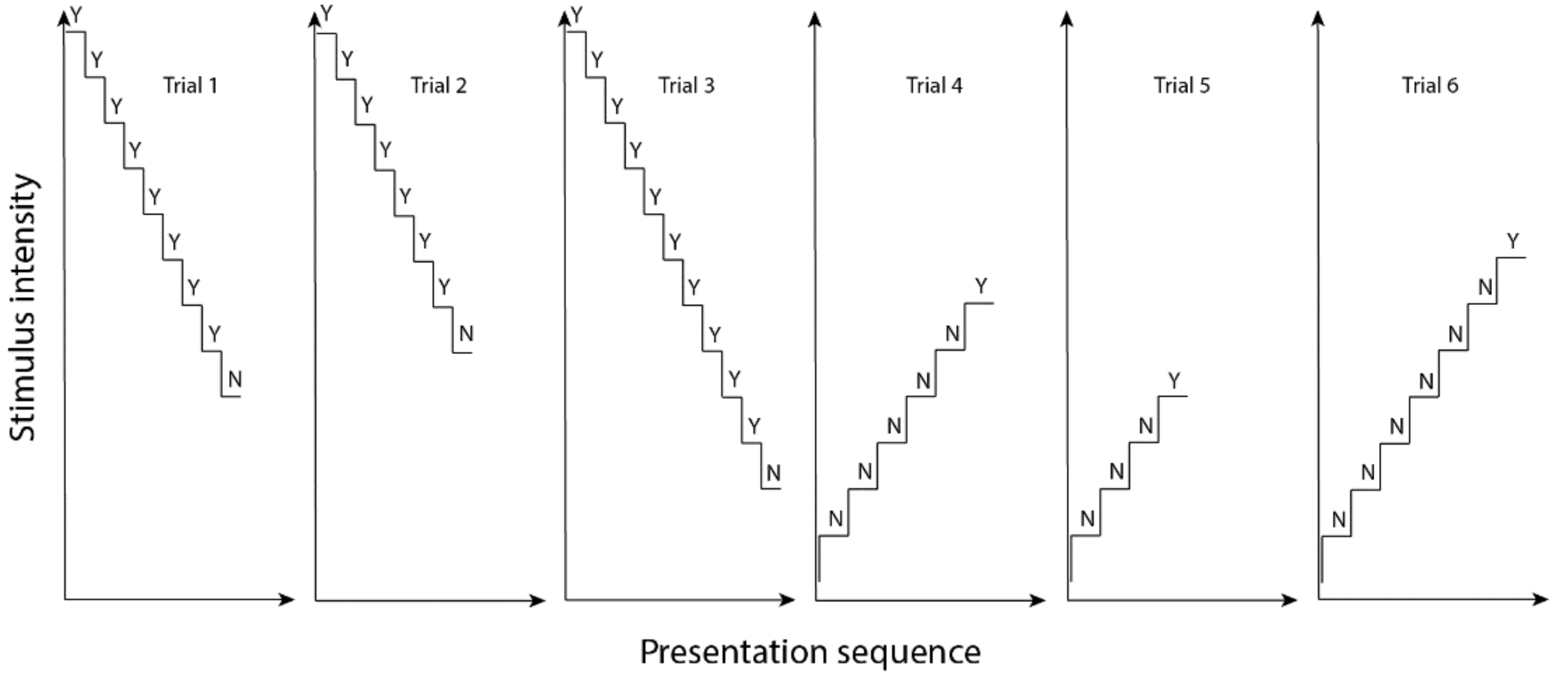
Method of limits

- The experiment ends when the observer reports the presence or absence of the expected sensation (a.k.a. the “limit”)
- Less precise but much faster
- Intensity should be separated by equal steps

Recipe:

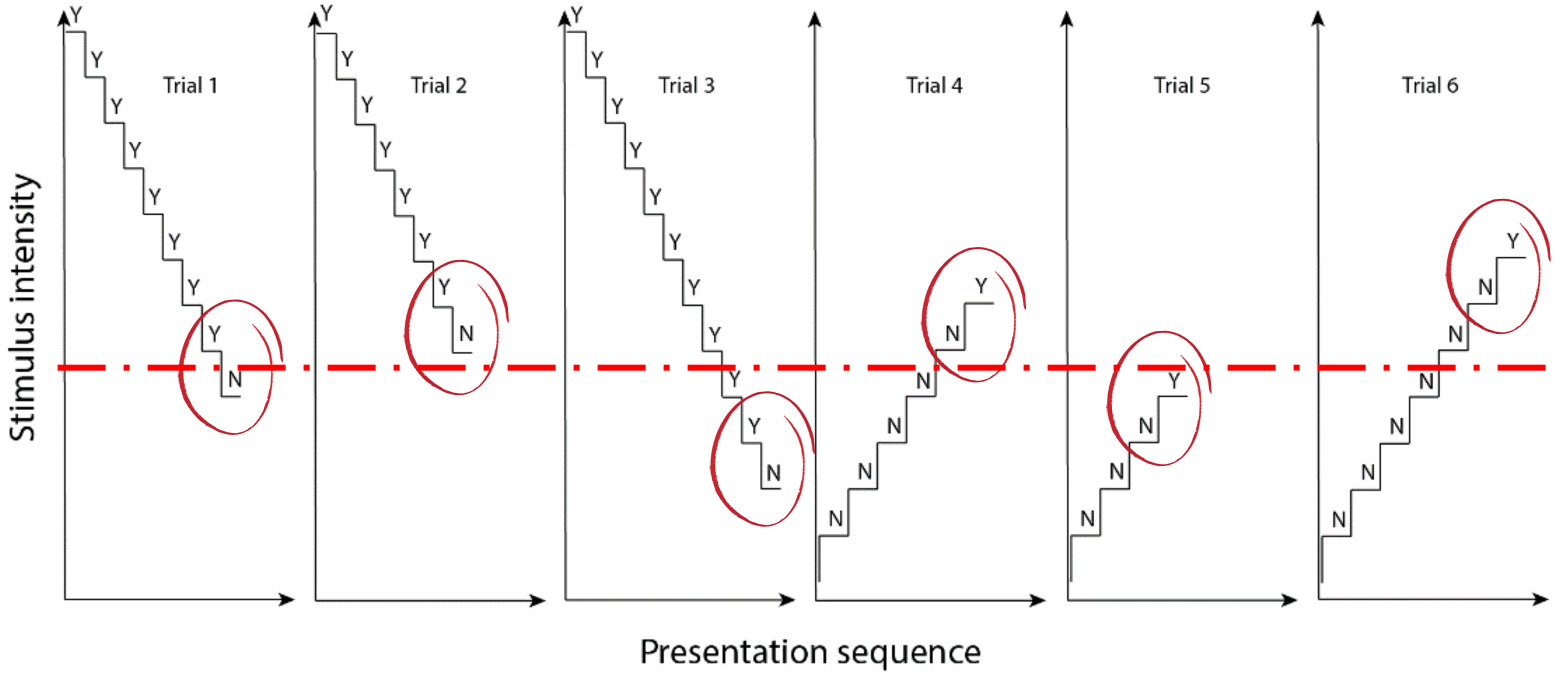
- Present the stimuli along upwards and downwards staircases
- Ask “do you perceive the stimulus?”
- Stop when the answer toggles

Method of limits



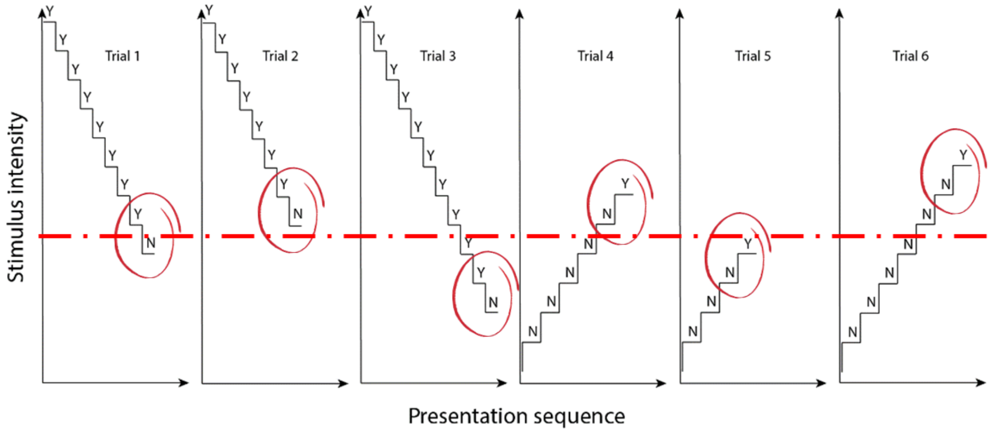
- Your results should end up looking like this…

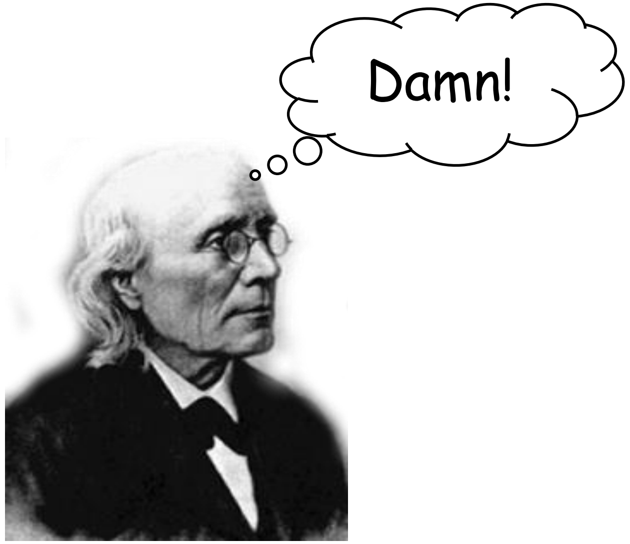
Method of limits



- The transition is midway
- Repeated using both ascending and descending series
- The threshold is obtained by averaging

Method of limits



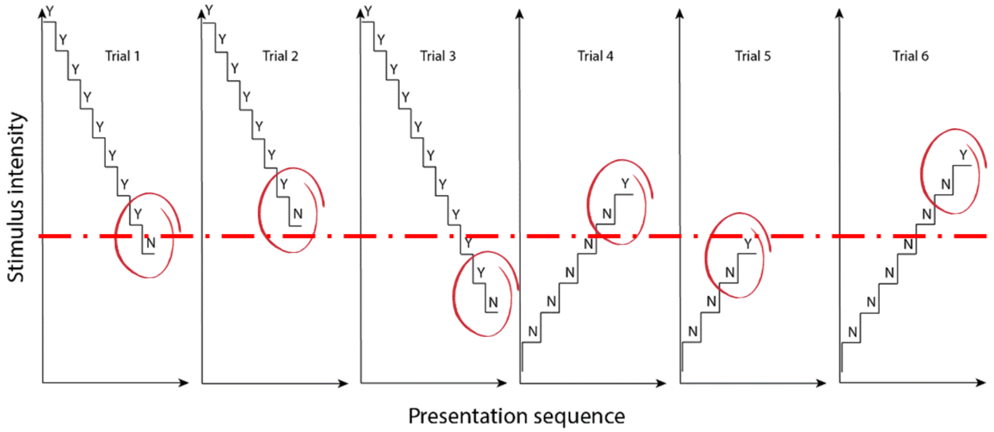


Disadvantages

Suffers from two systematic errors:

- Error of *habituation* (descending stimul)
- Error of *expectation* (ascending stimuli)
- The magnitudes of these complementary errors are not necessary the same

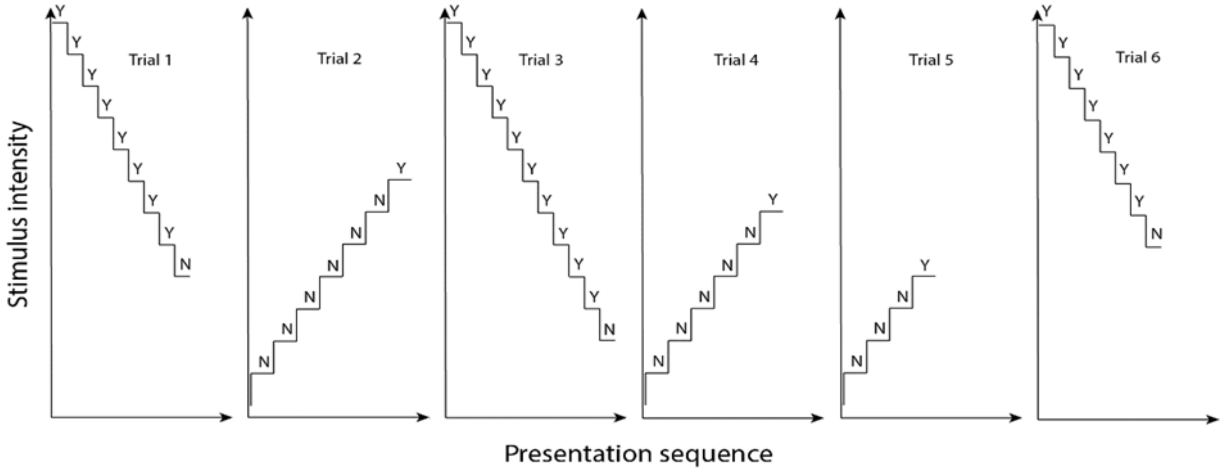
Method of limits



Solutions

- Varying the starting points of the staircases
- Alternating up and down staircases
- Switching directions, etc.

Method of adjustments



Same as before, except that…

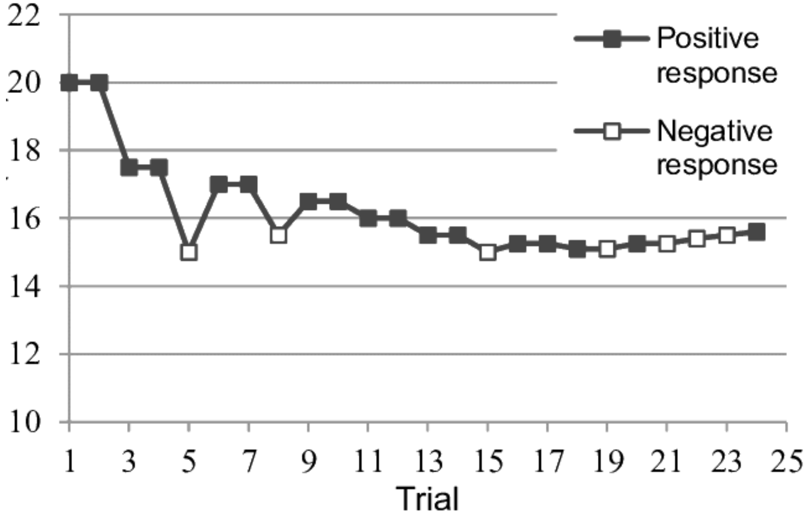
- Gives control to the observers
- Good when the task is tedious
- Good for a "quick & dirty" measure

- Also…
- Same shortcomings (biases) as the method of limits
- Alternates up and down directions, randomize starting points, etc.

Staircase procedures

Algorithms to optimize data collection

- Reduce the number of experimental trials by aiming at the threshold.
- Reverse their directions based on observer responses
- Start with a larger step size - reduced as the experiment reaches threshold
- Could be long and tedious for observers.



1-up-2-down staircase: one mistake = up; 2 correct = down

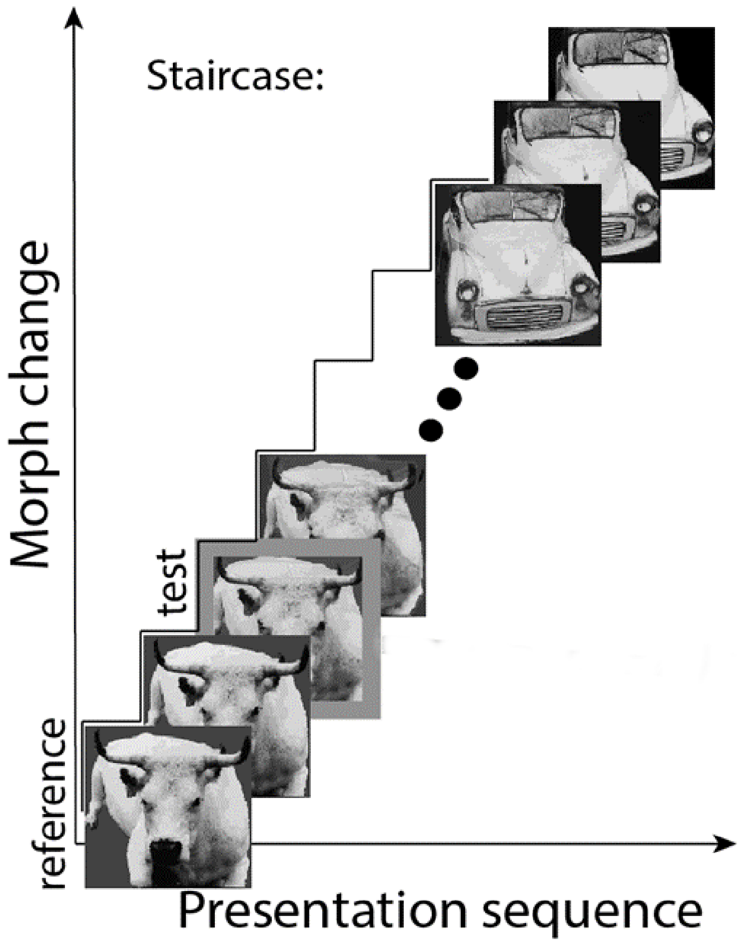
Problems with these methods

Beware of (human) observers!!

Observers are evil!

- They have biases (habituation, expectation, etc.)
- They usually try to predict what you want (you don't want that!)
- They may not understand the task
- They get tired
- Asking direct questions like "do you perceive the stimulus?" might not work...

Sometimes is better to give observers a task that they can do **only if they perceive the stimulus**

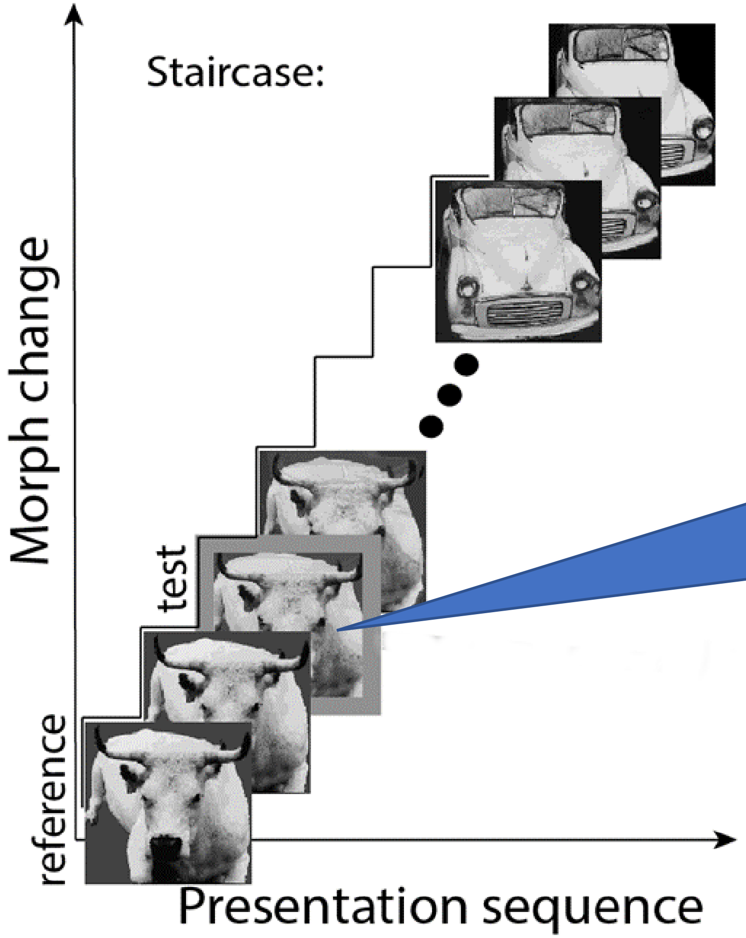


Example:

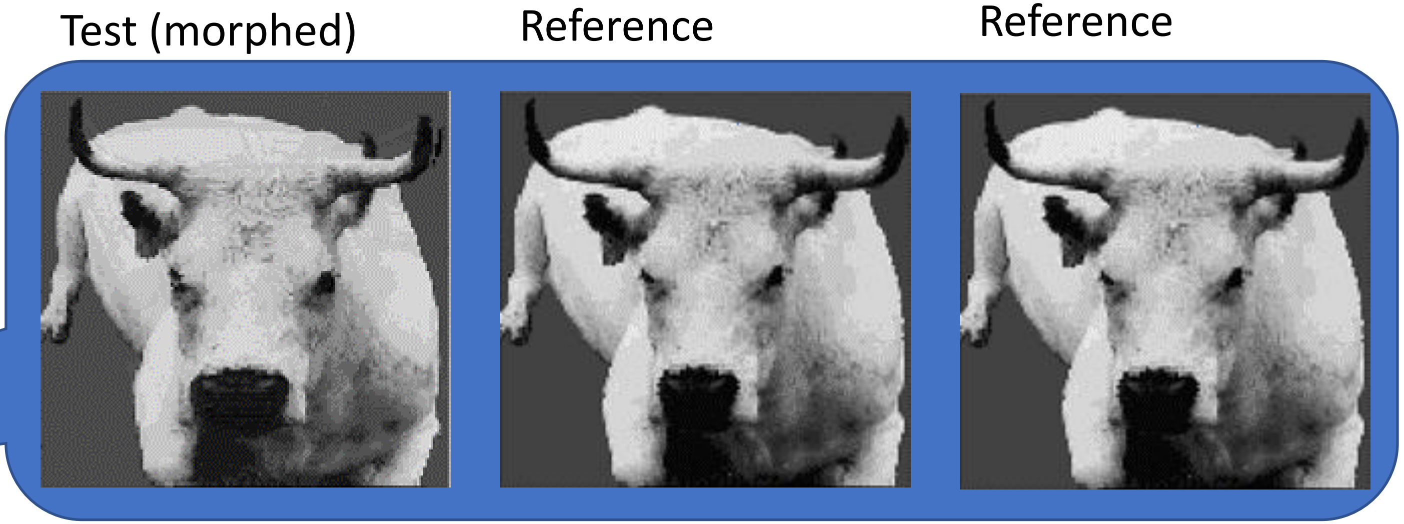
- Need to find out the “morph threshold”

Could ask “do you notice something odd?”

Sometimes is better to give observers a task that they can do **only if they perceive the stimulus**



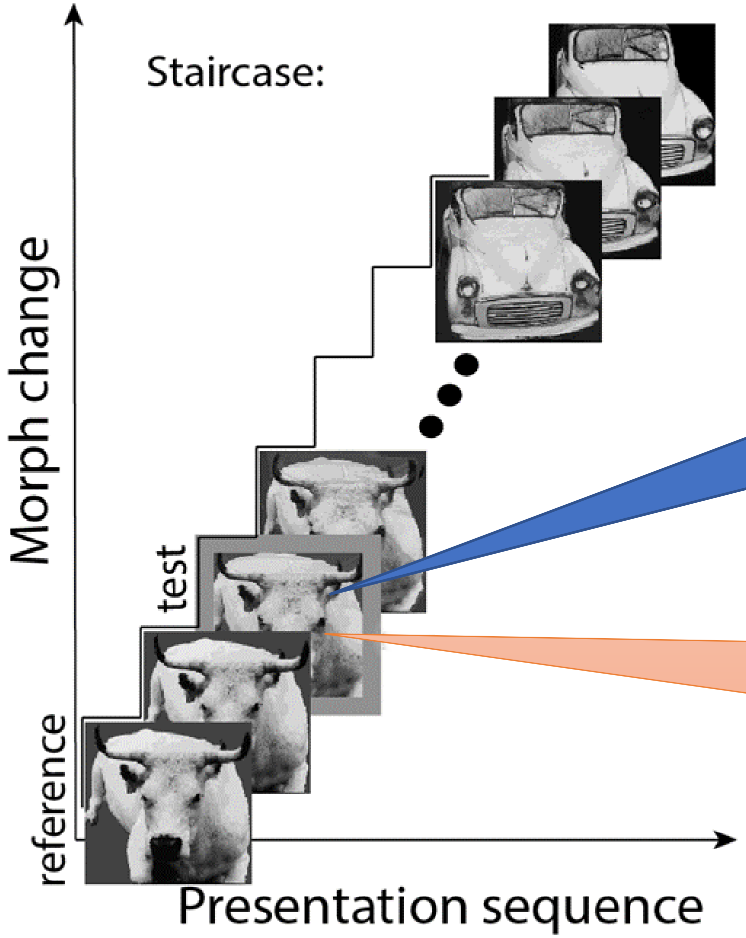
Example:

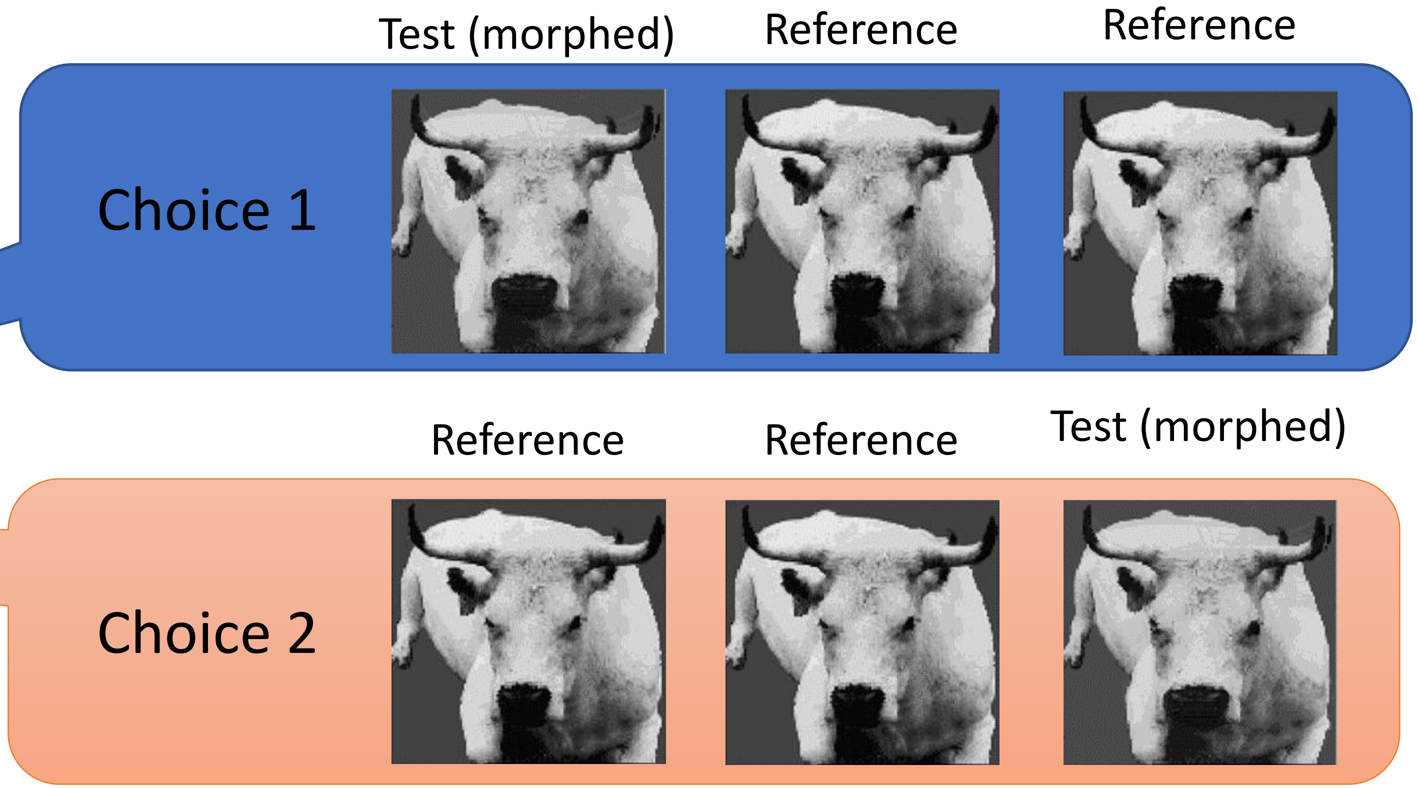


Which is the odd-one-out?

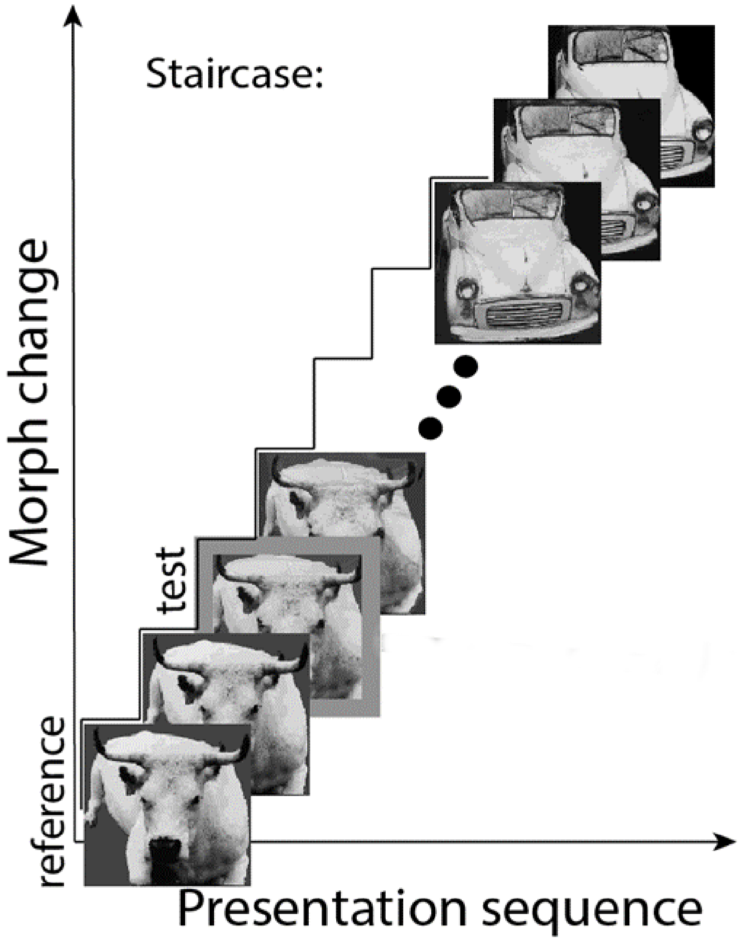
Which is the odd-one-out?

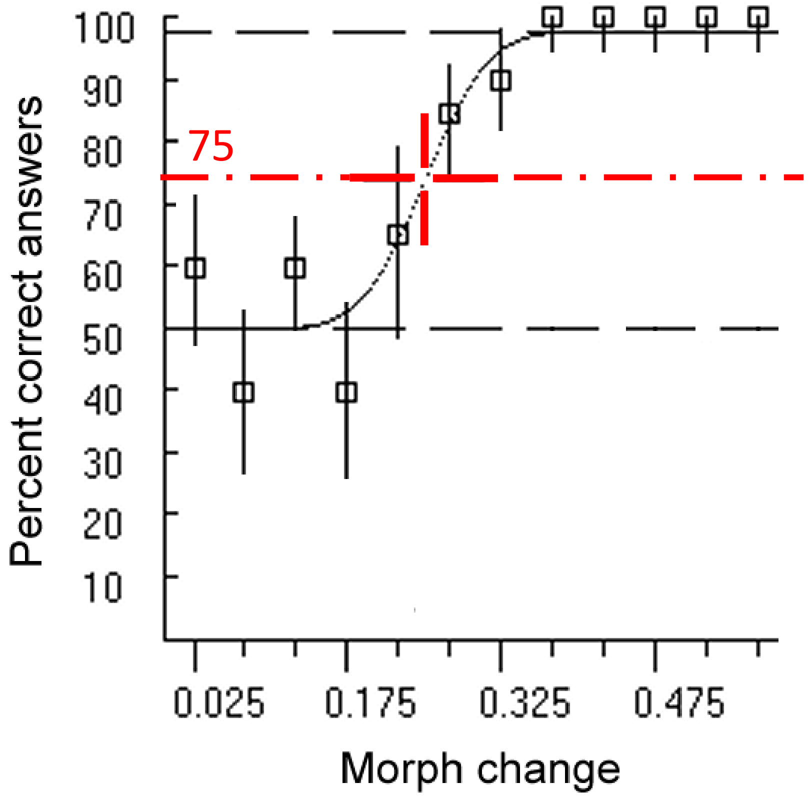
There are two choices at every step:





2-alternative forced choice procedure (2AFC)





- Lots of repetitions
- Precise
- Laborious

Bayesian and maximum-likelihood adaptive procedures

- Calculates the most probable estimate of the threshold and places the next trial there
- From the observer's perspective is similar to a staircase procedure
- More time consuming for the observer but more robust.
- Best known are QUEST (Watson & Pelli) and PEST (Harvey)

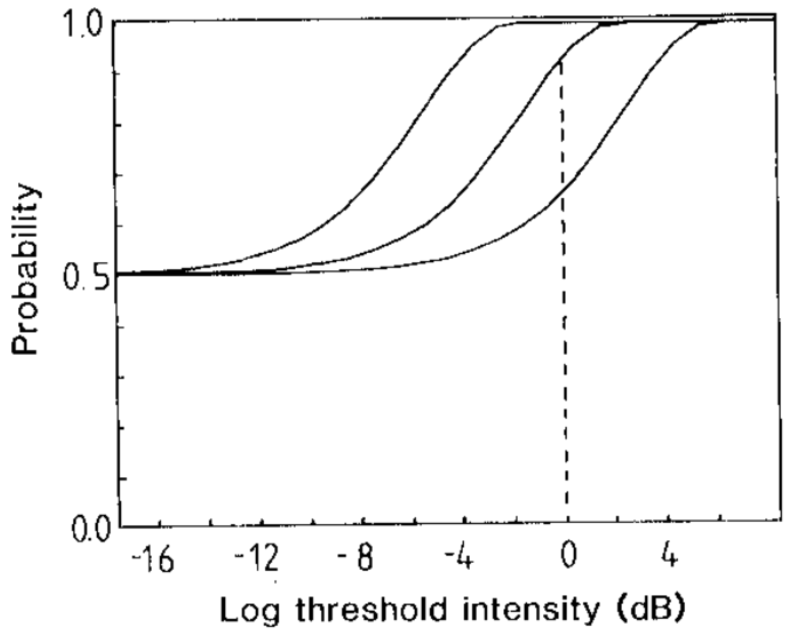
Garcıa-Perez, M. A. (1998). Forced-choice staircases with fixed step sizes: asymptotic and small-sample properties. Vision Research *38*, 1861–1881.

Bayesian adaptive procedures

$$p_T = min[1 - \delta, W_t(x)]$$

$$W_t(x) = 1 - (1 - \gamma)e^{-10^{\left(\frac{\beta}{20}\right)(x - T + \varepsilon)}}$$

- Weibull psychometric function
- Intensity (x) in dB (1 dB is a factor of $10^{1/20}$)
- γ (guess) probability of success at 0 intensity
- β is the slope of the psychometric function
- T (threshold) is a point with a pre-defined probability
- ε depends of the type of experiment
- δ = “finger mistakes”
- All these parameters are not “free” and must be chosen

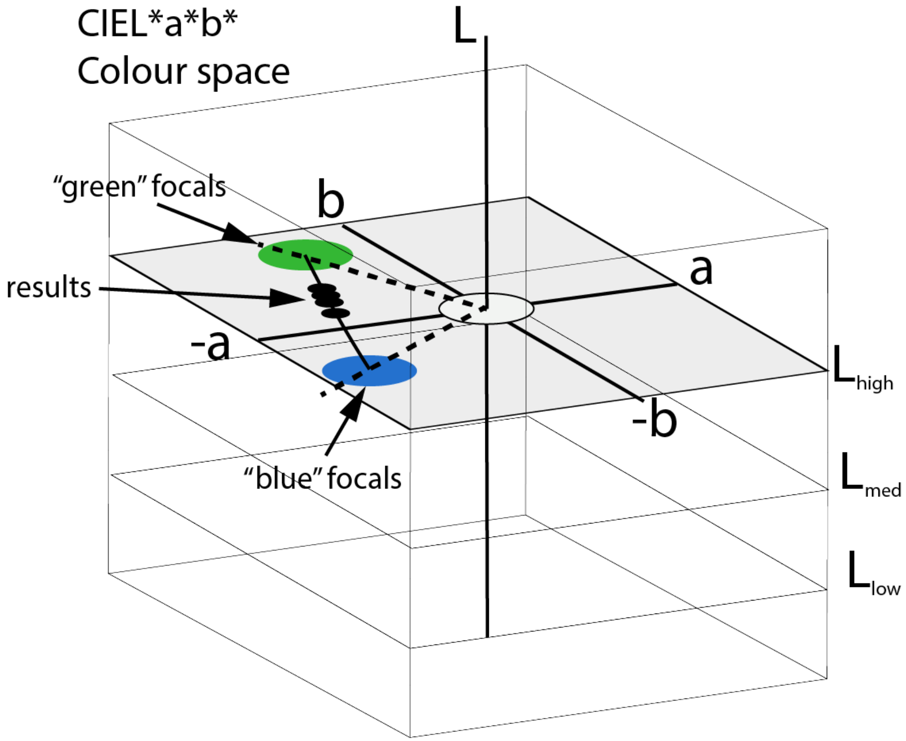


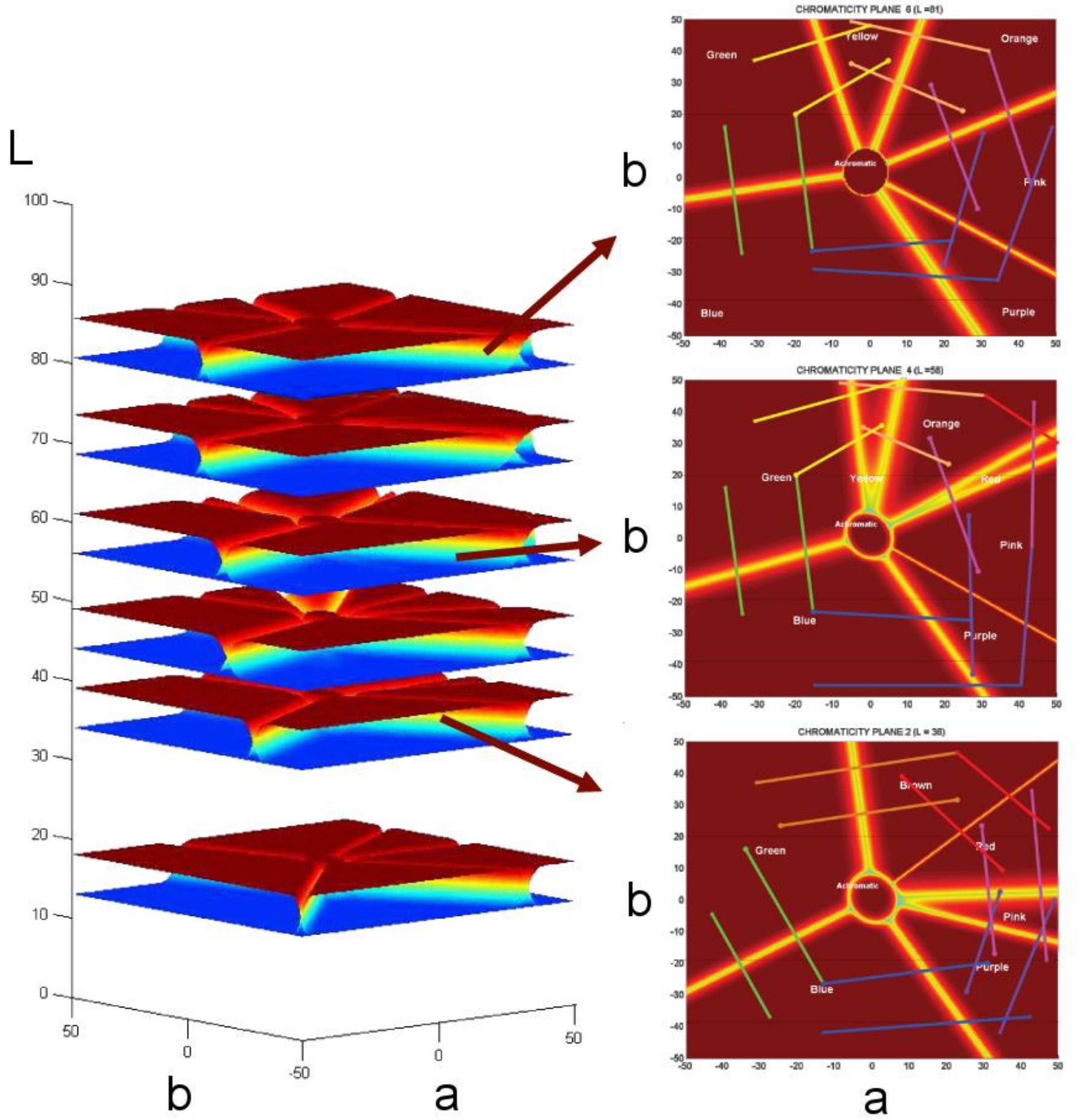
Garcıa-Perez, M. A. (1998). Forced-choice staircases with fixed step sizes: asymptotic and small-sample properties. Vision Research *38*, 1861–1881.

Cautionary tale on the importance of choosing the right method…

Colour names boundaries in CIELab colour space.

The same 2AFC procedure in a different context may not be the best…





Fuzzy membership regions proposed by Benavente *et al*. to segment the colour space, based on a product of sigmoids and an elliptical centre.

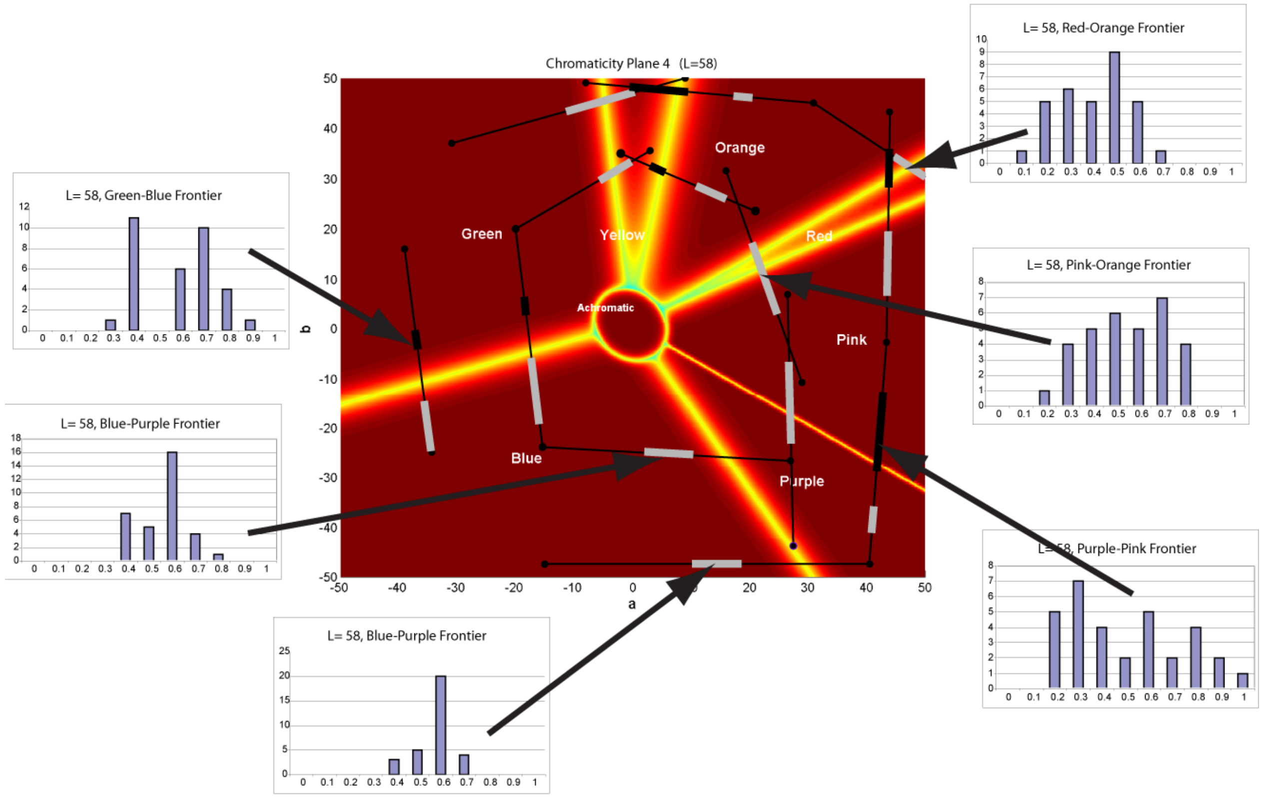
Colour names boundaries in CIELab colour space.

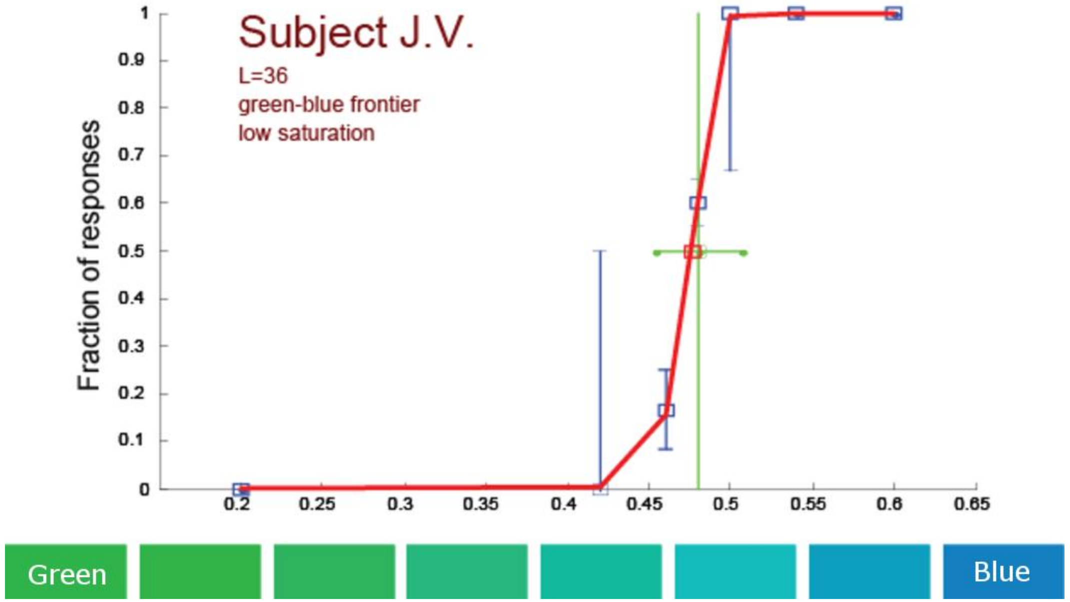
- 3 Lightness planes
- 2AFC-based staircase
- Asked subjects to name colours in the boundary regions
- Recorded the fraction of times a colour was named

R. Benavente, M. Vanrell, and R. Baldrich, A Data Set for Fuzzy Colour Naming. Color Research and Application, 31, 48-56. (2006).

Results:

- Large intra- and inter-subject variability…
- Some results were not repeatable even for the same subject in different occasions!
- Using such a precise method was an overkill!





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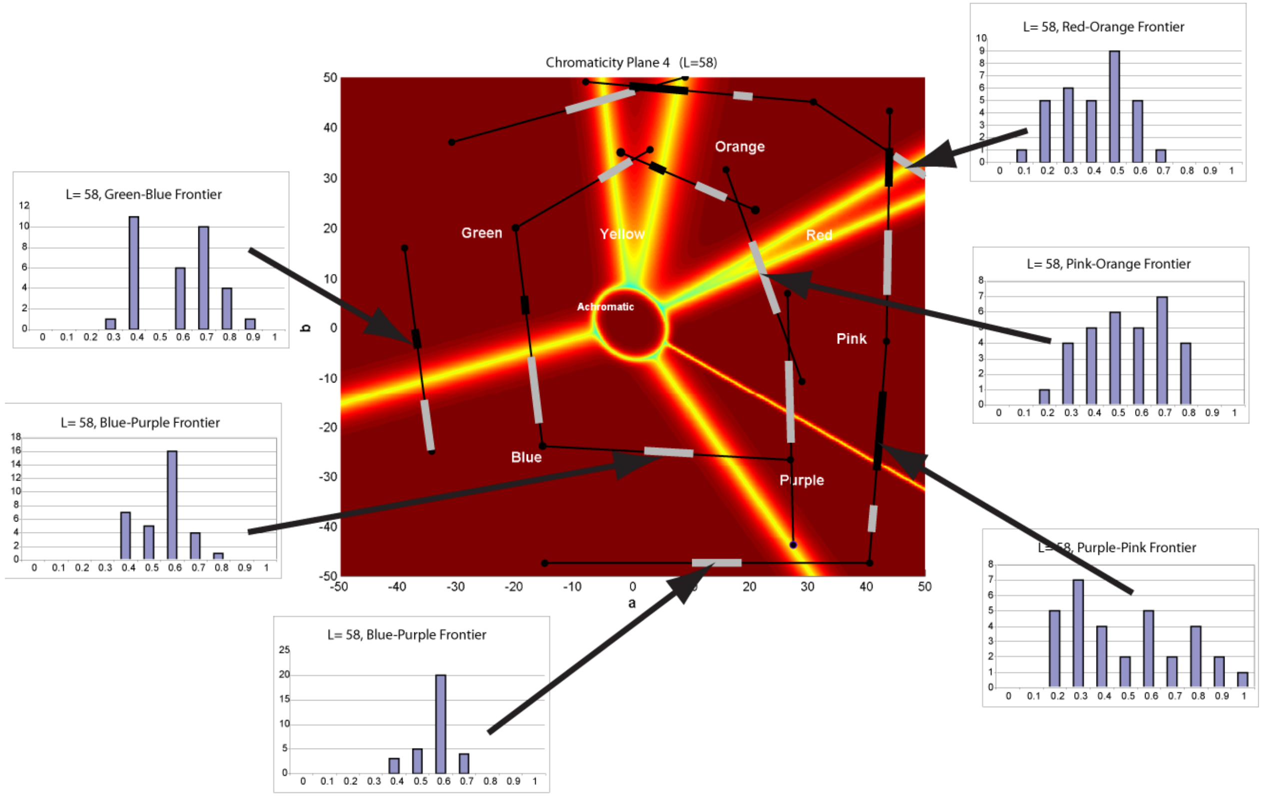
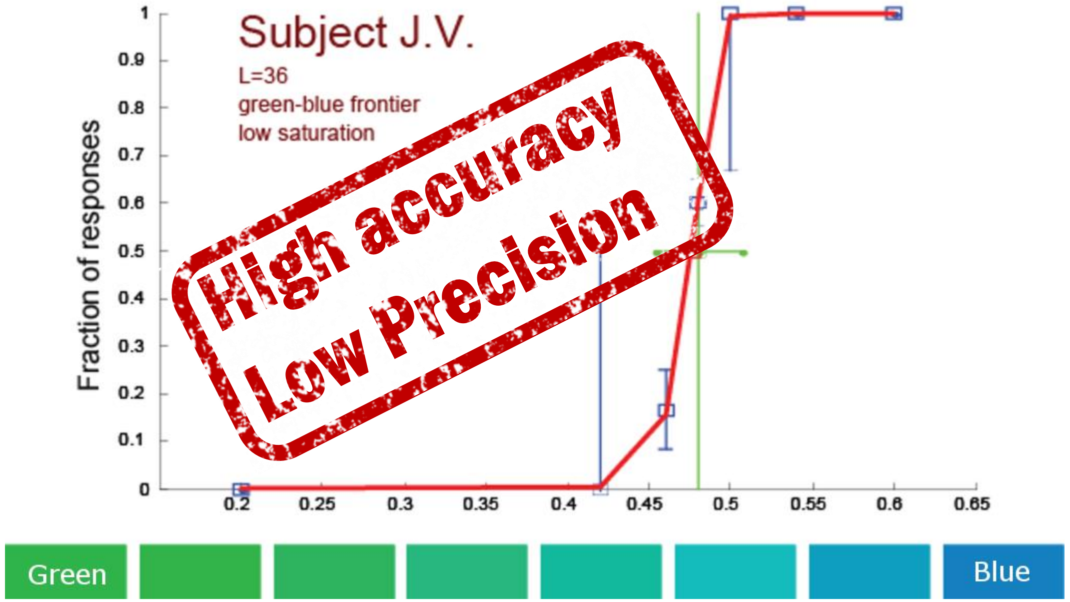
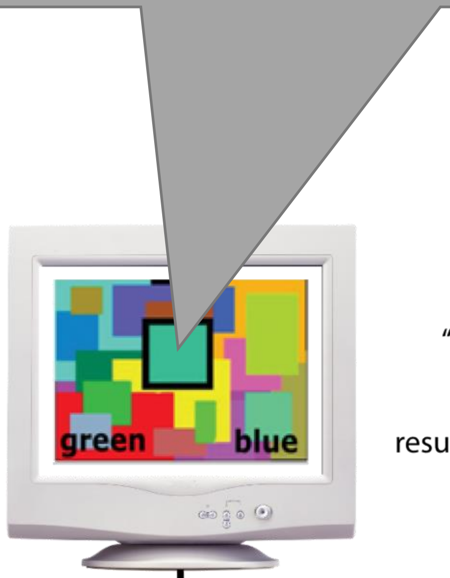
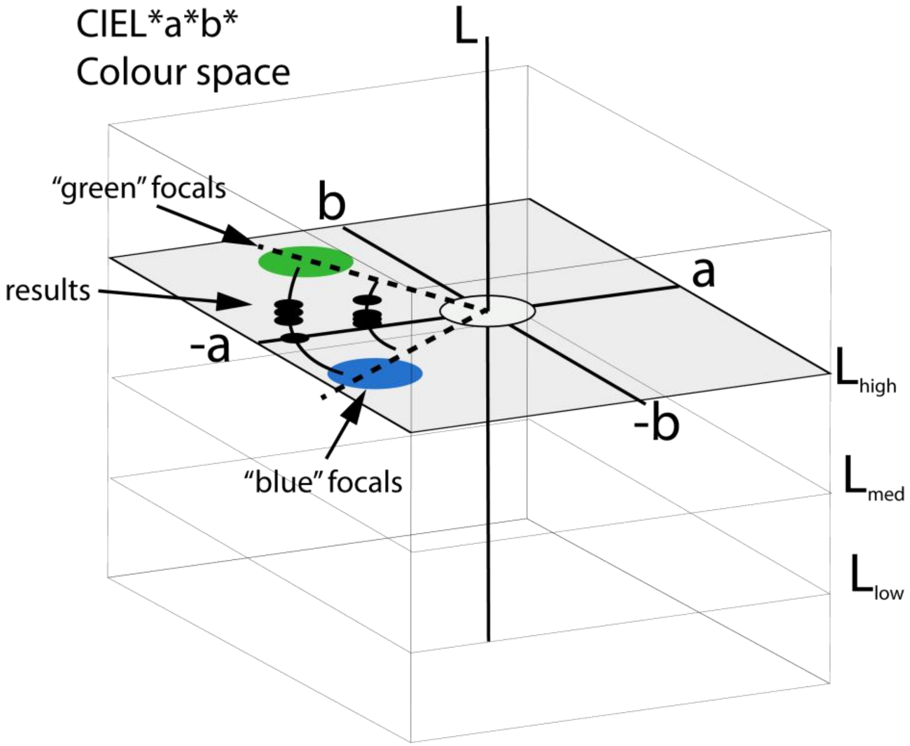




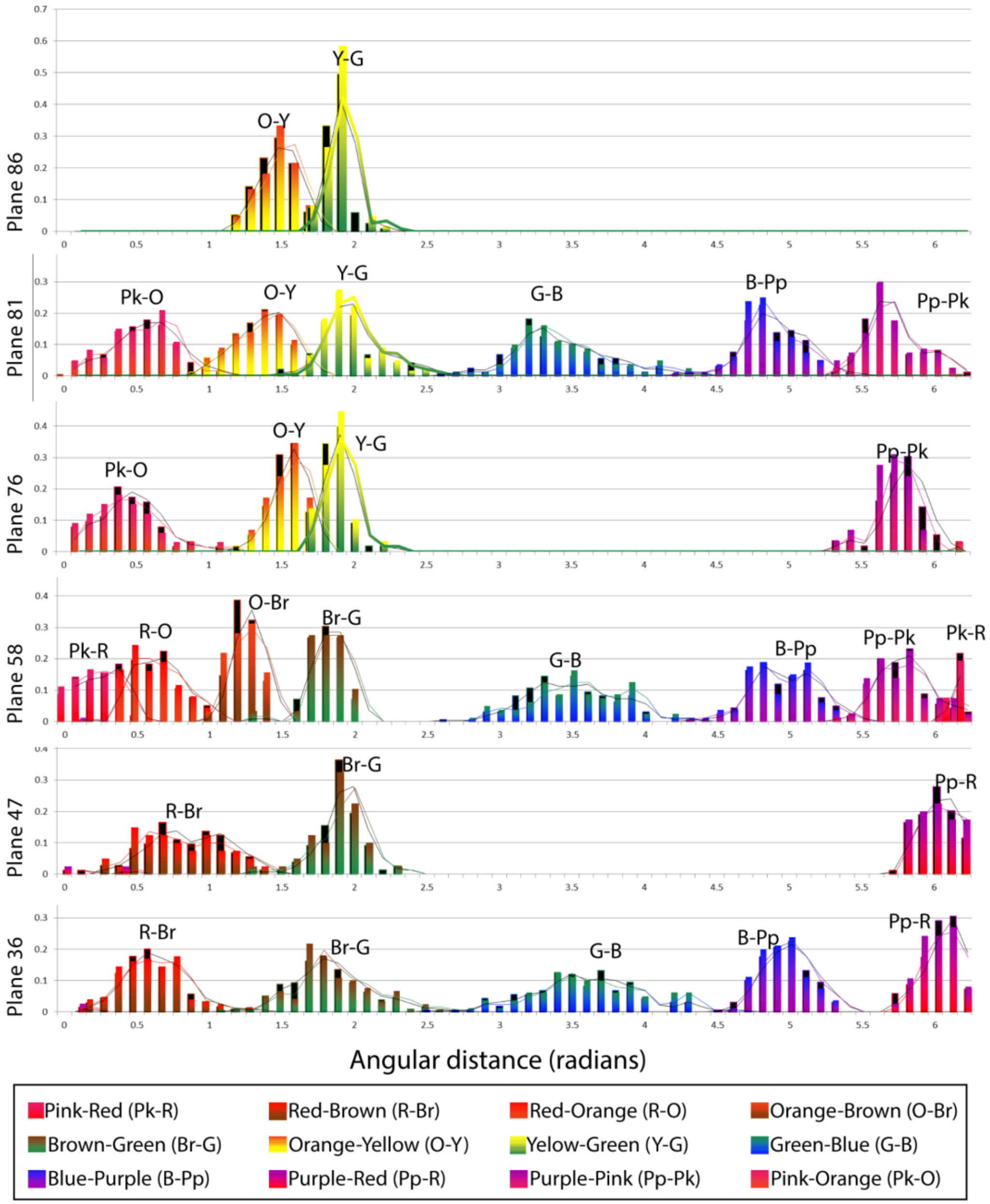
An alternative: method of adjustments

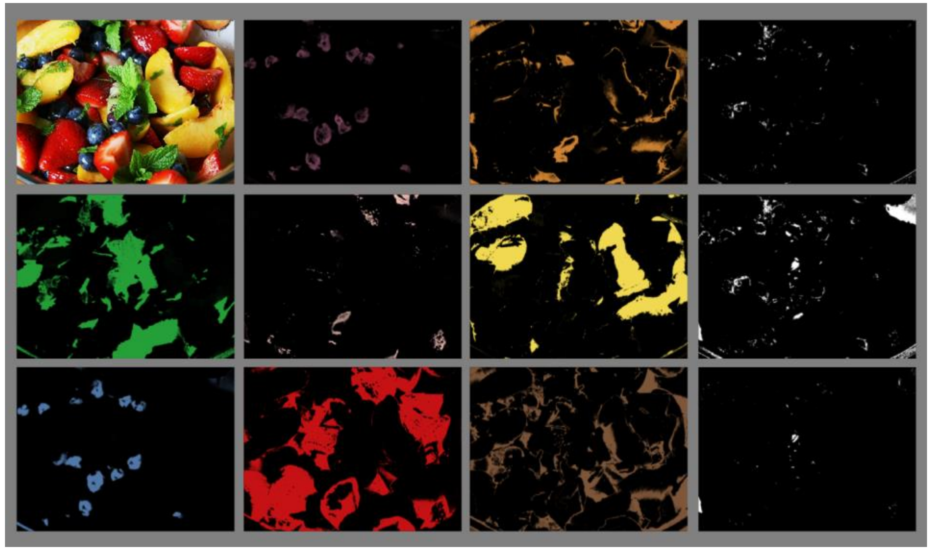
find a colour that is “midway between the two colours written at the bottom”

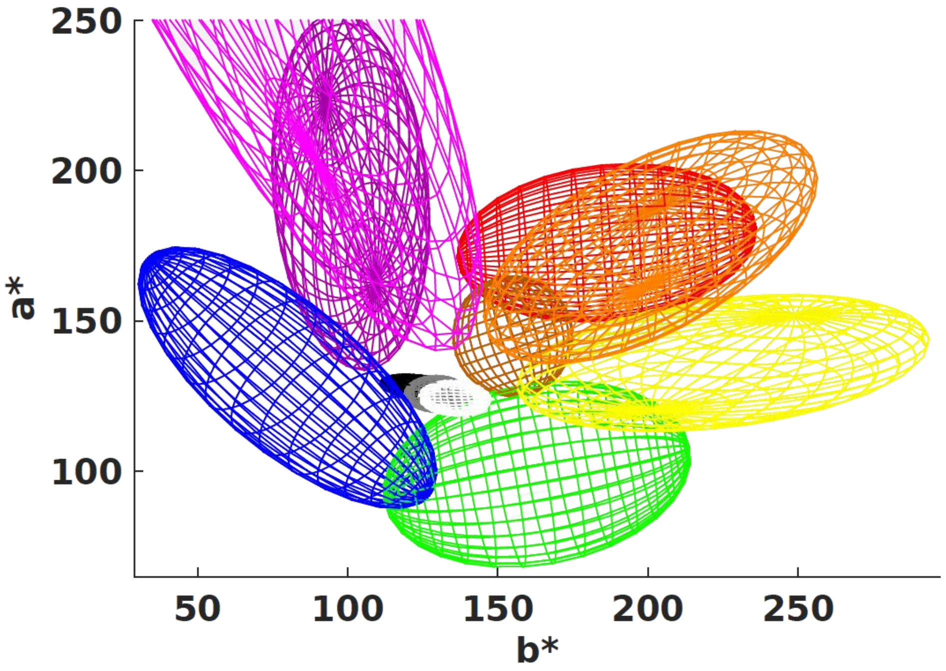




- 3 Lightness planes
- Subject controls the stimuli
- Asked subjects find the boundary
- Recorded the point where category changes
- Very fast (lots of points)


Plane 86
Y-G
O-Y
Plane 81
Pk-O
O-Y
Y-G
G-B
B-Pp
Pp-Pk
Plane 76
Pk-O
O-Y
Y-G
Pp-Pk
Plane 58
Pk-R
R-O
O-Br
Br-G
G-B
B-Pp
Pp-Pk
Pk-R
Plane 47
R-Br
Br-G
Pp-R
Plane 36
R-Br
Br-G
G-B
B-Pp
Pp-R
Angular distance (radians)
Pink-Red (Pk-R)
Red-Brown (R-Br)
Red-Orange (R-O)
Orange-Brown (O-Br)
Brown-Green (Br-G)
Orange-Yellow (O-Y)
Yelow-Green (Y-G)
Green-Blue (G-B)
Blue-Purple (B-Pp)
Purple-Red (Pp-R)
Purple-Pink (Pp-Pk)
Pink-Orange (Pk-O)



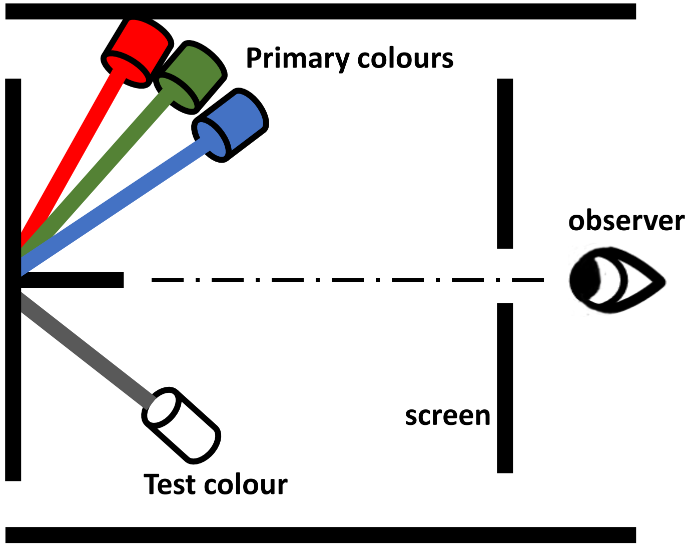

a*
b*
250
200
150
100
50
100
150
200
250

Matching

The subject's task is to adjust one of two stimuli so that they are perceived the same in some respect.

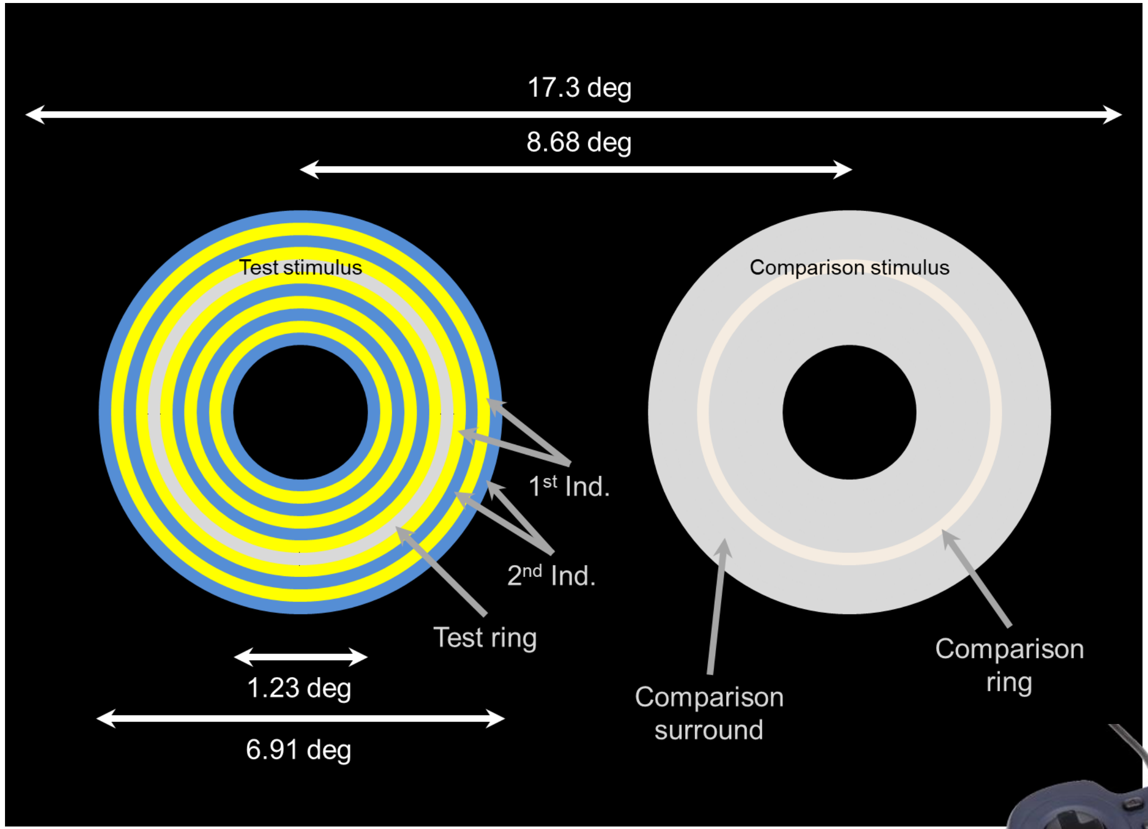
Various configurations, ex.

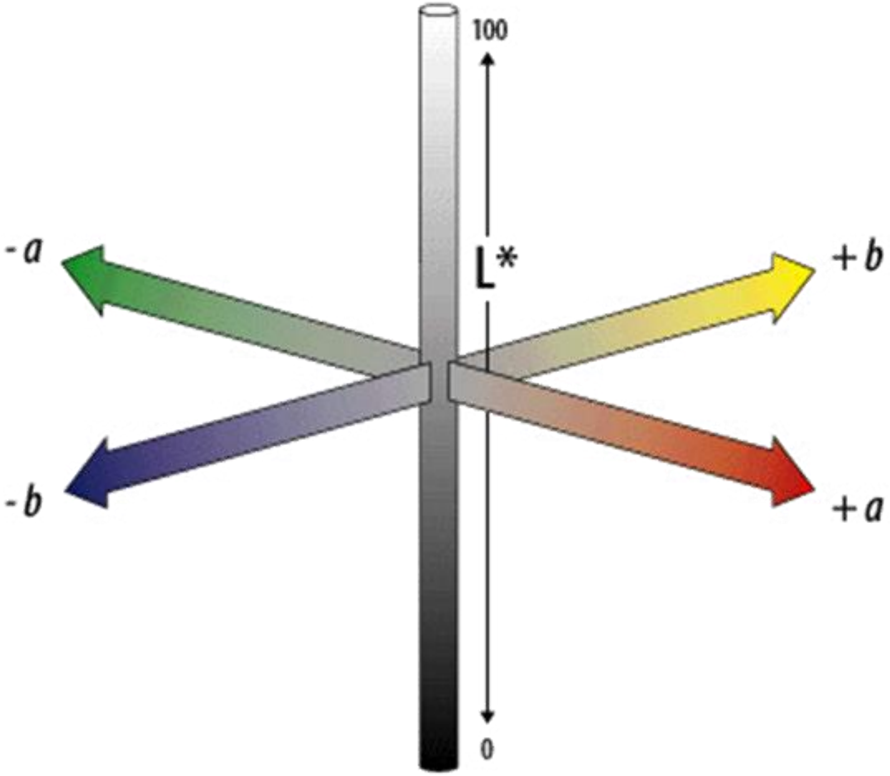
- Adjust the brightness of one sample until is equal to the brightness of another.
- From a series of trials consisting of pairs of colour samples, pick the one where the colours are closest, etc.



Matching with onscreen stimuli

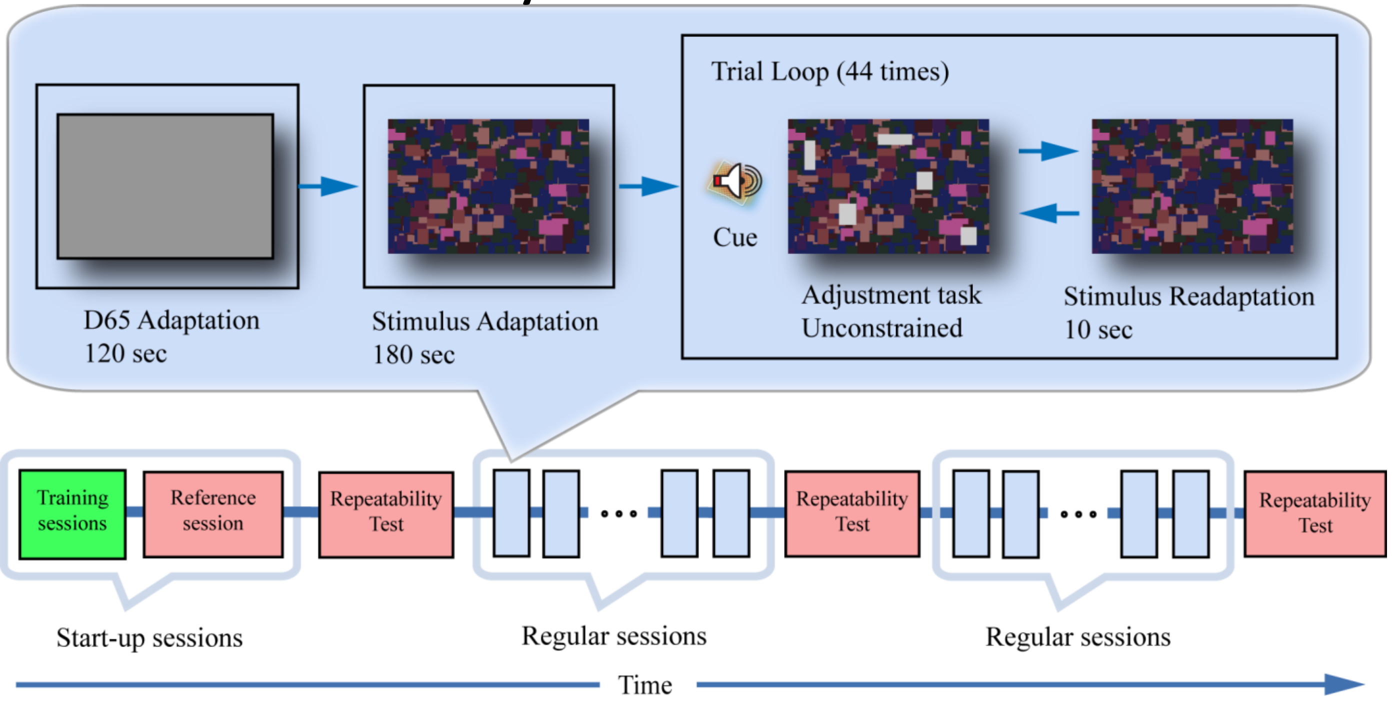
Chromatic induction

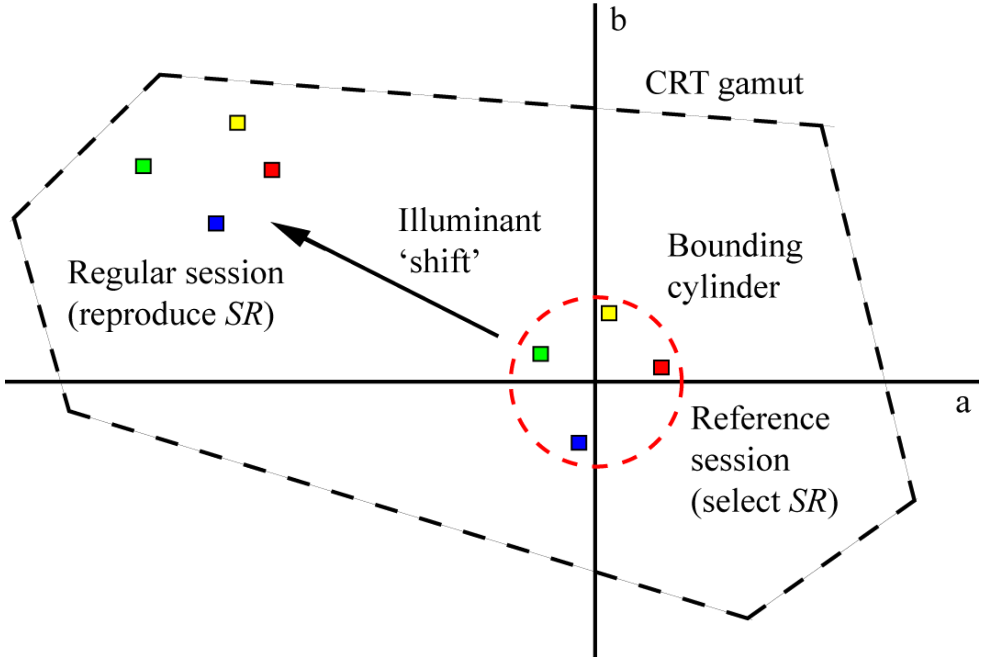




Matching with memorised stimuli

Colour Constancy





Practical advise

- Pick the right tools for the job
  - Right instruments
  - Right paradigm
- Train your subjects
- Do perform pilot experiments
- Watch out for subject's mistakes
  - Tiredness
  - Misunderstanding of the instructions
  - Laziness
- Get a lucky charm…

Thank you!

My psychophysics lab:

How I see it…

How my postdocs see it…

How my subjects see it…