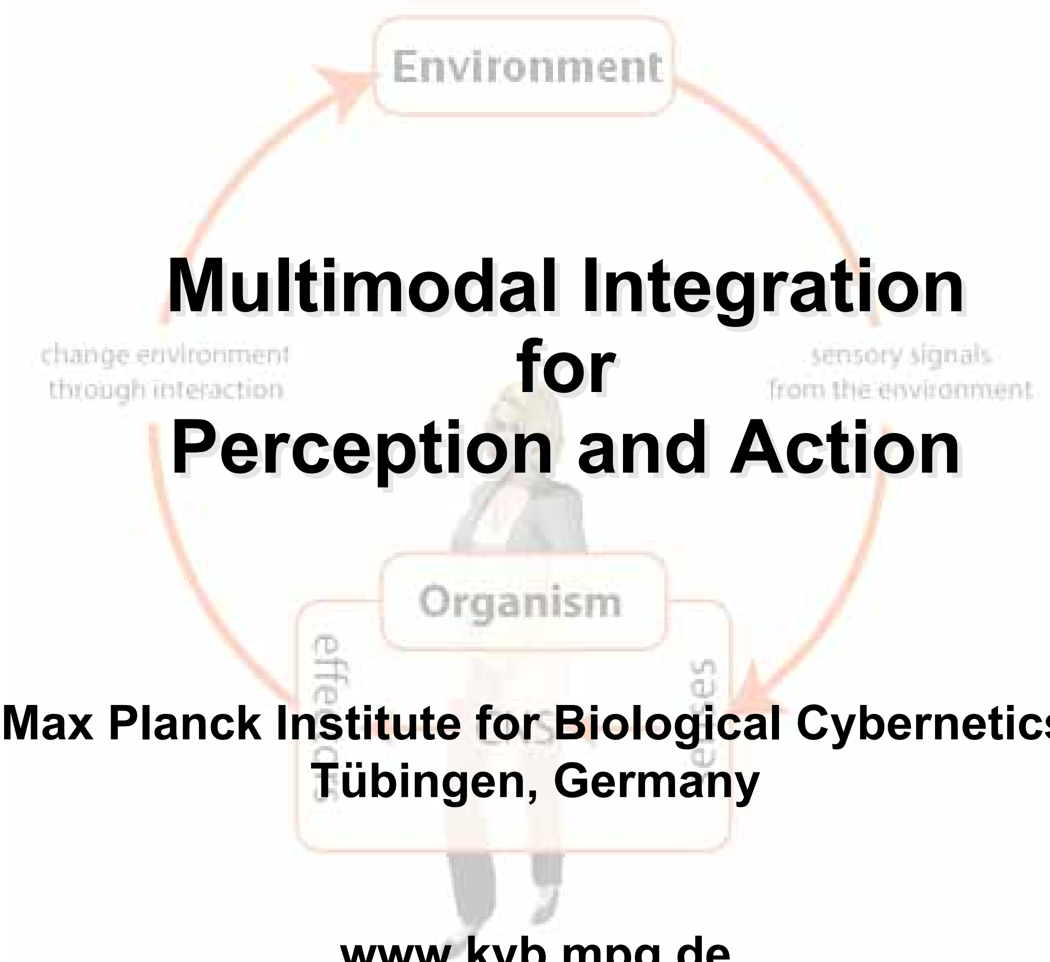
MAX-PLANCK-GESELLSCHAFT

MPI FOR BIOLOGICAL CYBERNETICS

Heinrich H. Bülthoff



Multimodal Integration for Perception and Action

Max Planck Institute for Biological Cybernetics
Tübingen, Germany

www.kyb.mpg.de

Outline

- Sensor fusion at an Early Level
  - Uni-modal Integration (Vision)
    - Shape-from-X (stereo, shading, texture, motion)
  - Multi-modal Integration
    - Visual-Haptic
    - Visual-Vestibular
    - Visual-Auditory
- Sensor fusion at a Higher Level
  - Effects of Attention and Awareness on Integration
- Integration for Control Tasks
  - Multimodal integration for novel ego-motion simulators

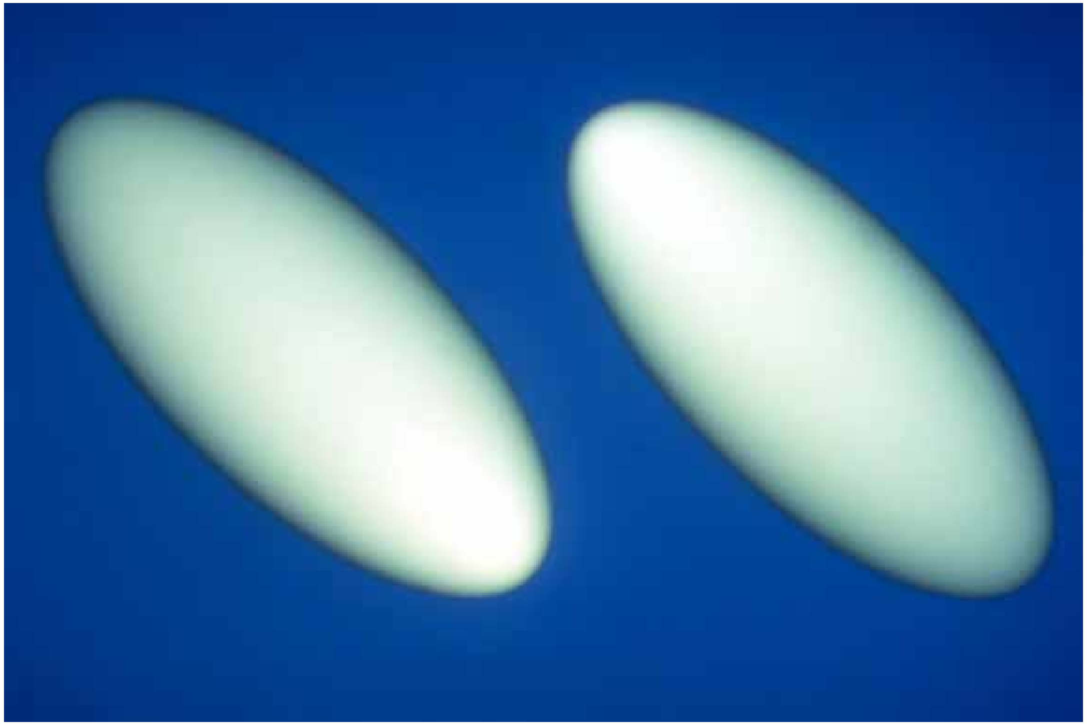
Early Sensor Fusion

examples from vision studies

Bülthoff, Mallot, Blake, Yuille,…(1985-1993)

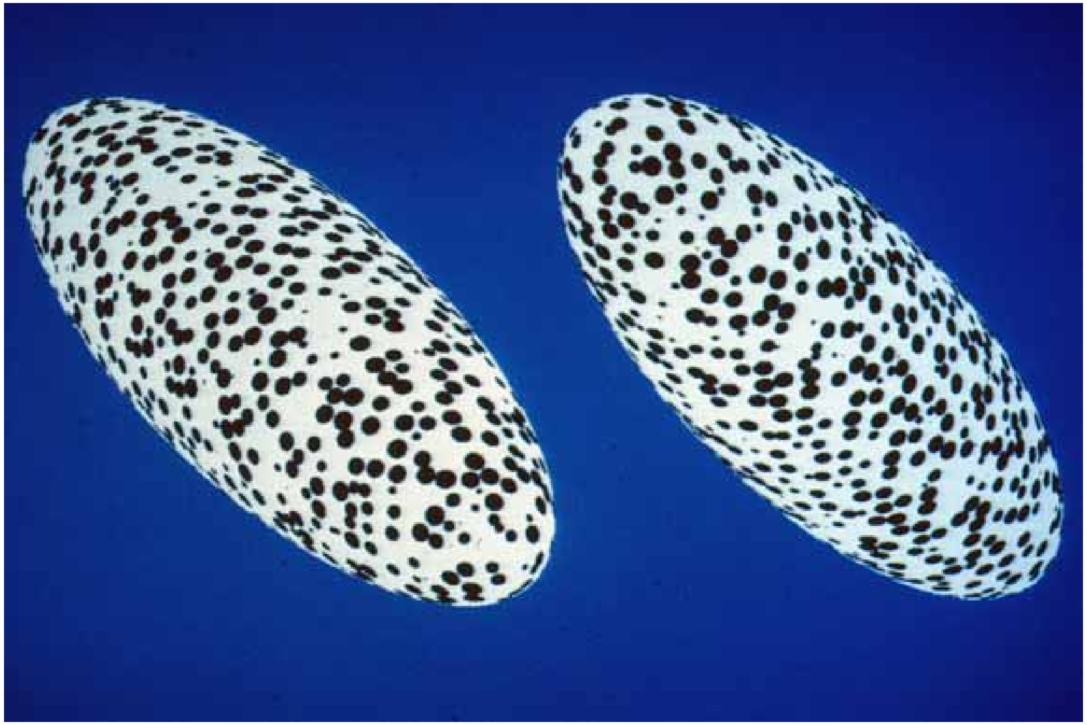
- **accumulation** (the-more-the-better policy)
  - linear combination of shape-from-x modules
  - joint regularization (with cost function)
- **cooperation or strong fusion**
  - likelihood functions for individual cues are often not independent
  - shape-from-shading and shape-from-texture are weak cues
  - combined they provide almost perfect shape perception

Shape-from-Shading



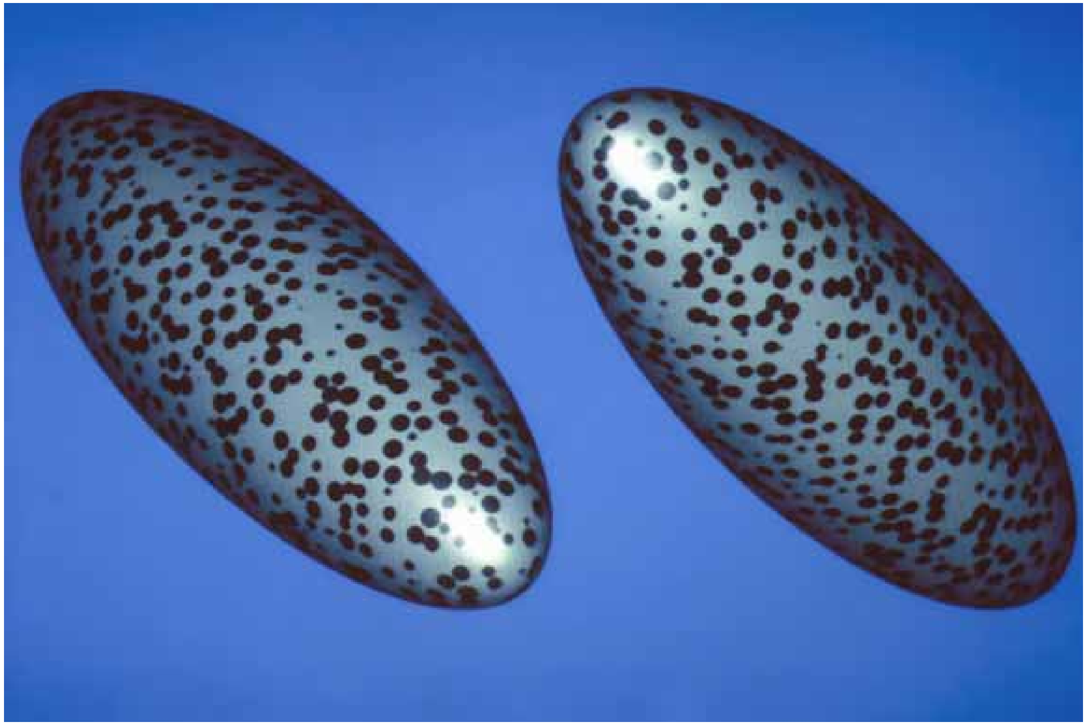
Shape-from-shading is a weak cue
to the perception of orientation.

Shape-from-Texture



Shape-from-texture is a weak cue
to form and orientation.

Shading + Texture



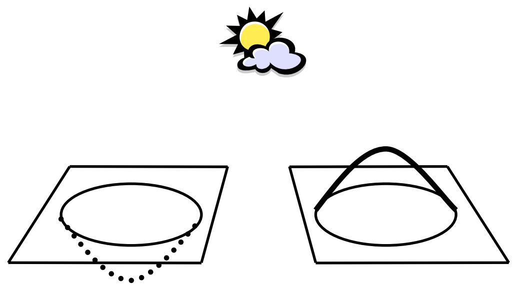
Integration of all cues provides good perception of form and orientation.

Early Sensor Fusion

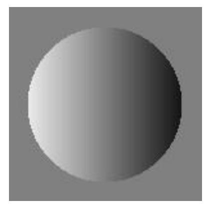
- **accumulation** (the-more-the-better policy)
  - linear combination of shape-from-x modules
  - joint regularization (with cost function)
- **cooperation or strong fusion**
  - likelihood functions for individual cues are often not independent
  - shape-from-shading and shape-from-texture are weak cues
  - **combined they provide almost perfect shape perception**
- **disambiguation**
  - stereo can disambiguate shading (convex / concave)

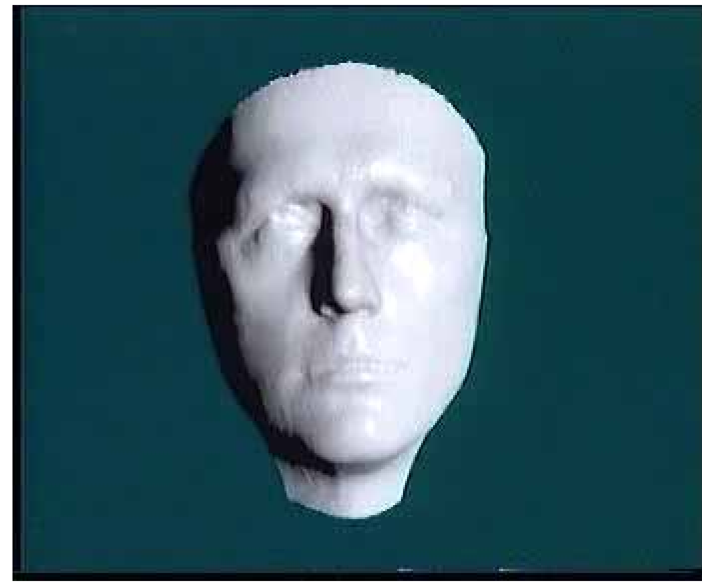
Disambiguation

shape-from-shading is ambiguous



valley hill

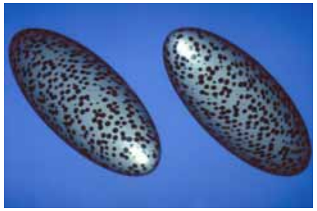




- **convexity prior** (familiarity) dominates ambiguous interpretation
  - ***Langer, M.S. and H.H. Bülthoff:*** A prior for global convexity in local shape-from-shading. Perception **30**, 403-410 (2001)
  - ***Langer, M.S. and H.H. Bülthoff:*** Depth discrimination from shading under diffuse lighting. Perception **29**, 649-660 (2000)
- **stereo disambiguates** shape-from-shading

Sensor fusion of visual modules

- **accumulation** (the-more-the-better policy)
  - linear combination of shape-from-x modules
  - joint regularization (with cost function)
- **cooperation or strong fusion**
  - likelihood functions for individual cues are often not independent
  - shape-from-shading and shape-from-texture are weak cues
  - combined they provide almost perfect shape perception
- **disambiguation**
  - stereo can disambiguate shading (convex / concave)
- **veto**
  - very strong cues should not be challenged by others
  - edge-based stereo vetoes intensity-based stereo



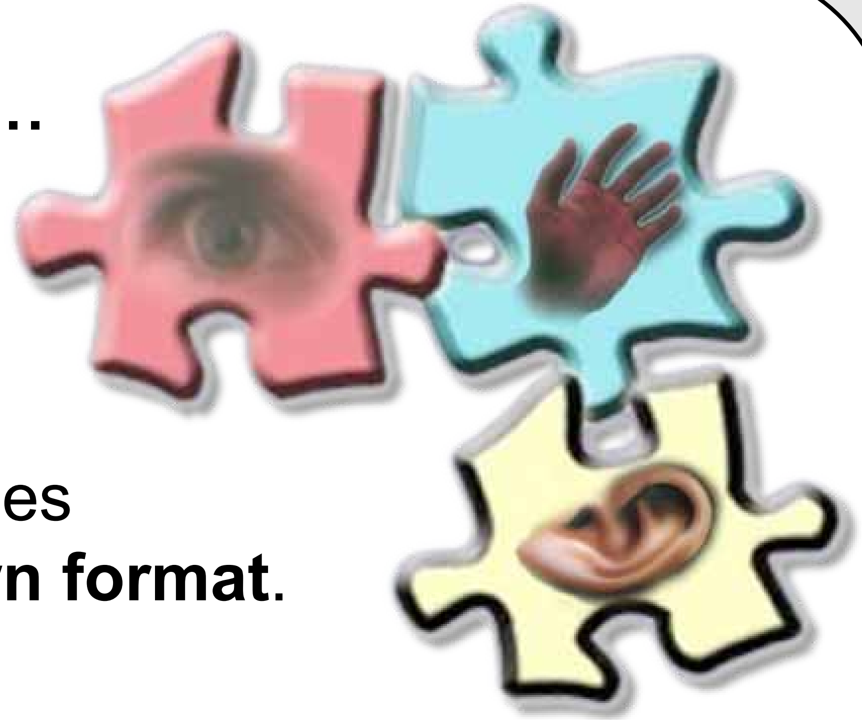
Bülthoff, H.H. and H.A. Mallot: Integration of depth modules: stereo and shading. Journal of the Optical Society of America 5, 1749-1758 (1988)

Blake, A. and H.H. Bülthoff: Does the brain know the physics of specular reflection? Nature 343, no. 6254, 165-168 (1990)

Bülthoff, H.H.: Shape from X: Psychophysics and Computation. Computational Models of Visual Processing, M. Landy and A. Movshon Eds., M.I.T. Press, 305-330 (1991)

Multimodal Sensor Fusion
The Puzzle of the Senses

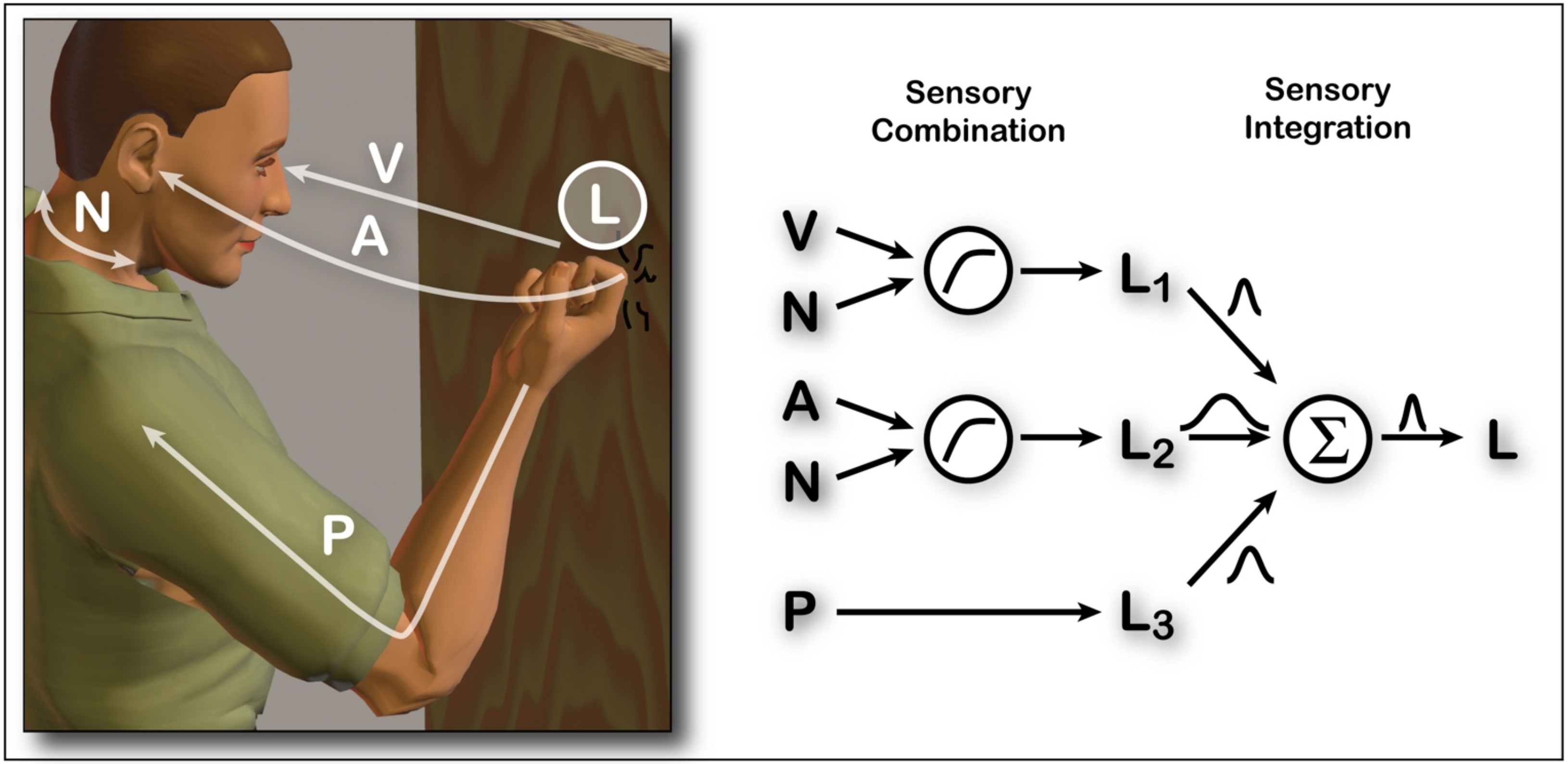
Vision, Touch, Audition, ...



Each sensory modality provides **unique information** in its **own format**.

How is all this sensory information put together to form a coherent percept?

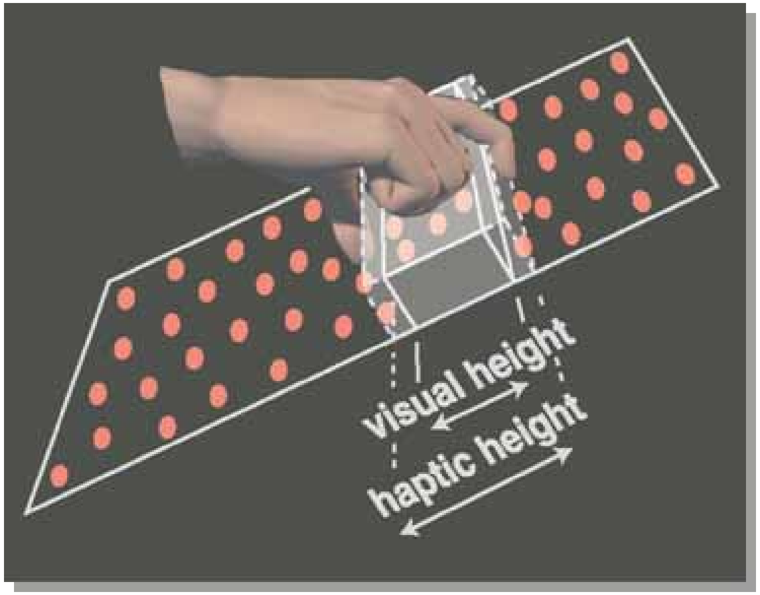
Forming a Unique Percept



M. Ernst & H. Bülthoff, TICS 2004

The problem of sensory integration

Size estimation with vision and touch



Physics

Vision: photons striking retinas

Haptics: changing pressure on fingers

Sensor bias & noise

Systematic bias: between senses arises from consistent distortion (e.g., glasses or gloves)

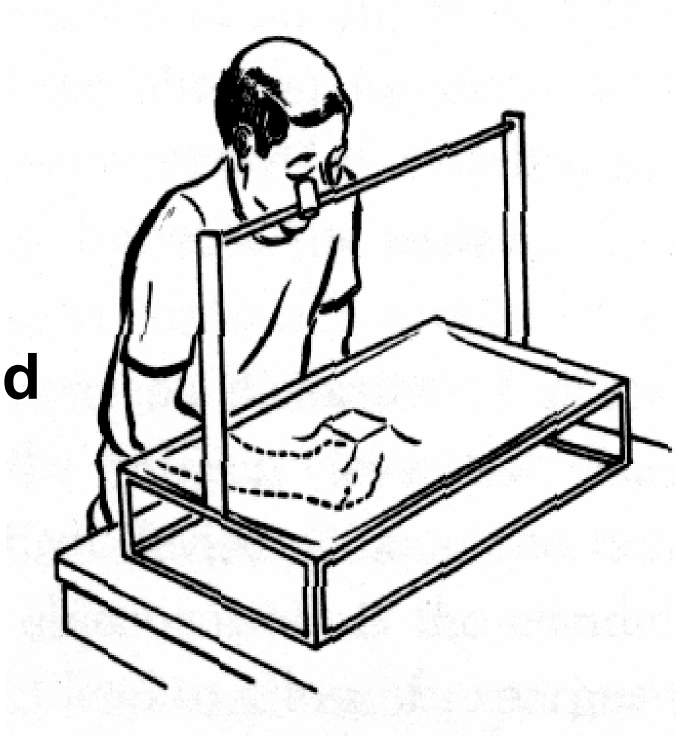
Unsystematic bias: arises from measurement noise

What is the optimal way to integrate sensory information?

Multimodal Cue Integration
Rock & Victor (1964)

Irv Rock

View cube through distorting lens while exploring object haptically.

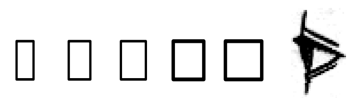
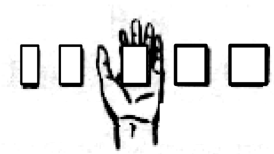


Visually and haptically specified shapes differ.

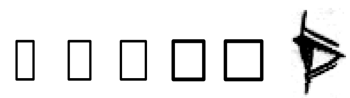
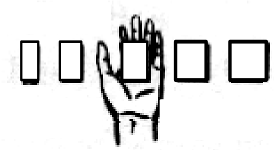
What shape is perceived?

Cube or elongated box ?

Rock & Victor (1964) Experimental Design

Stimulus Presentation			Response Method
Vision alone	Haptic alone	Conflict	
V	*H*	*V* *H*	Drawing 
V	*H*	*V* *H*	Vision alone 
V	*H*	*V* *H*	Haptic alone 

Rock & Victor (1964) Results

Stimulus Presentation			Response Method
Vision alone	Haptic alone	Conflict	
V 1.90	*H* 0.98	*V* *H* 1.85	Drawing 
V 13.4	*H* 23.1	*V* *H* 14.1 mm	Vision alone 
V 14.1	*H* 20.5	*V* *H* 14.5 mm	Haptic alone 

Rock & Victor (1964)
Results

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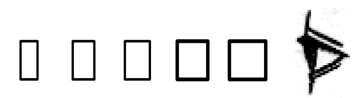
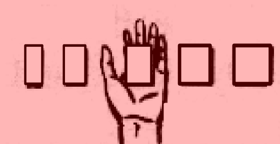
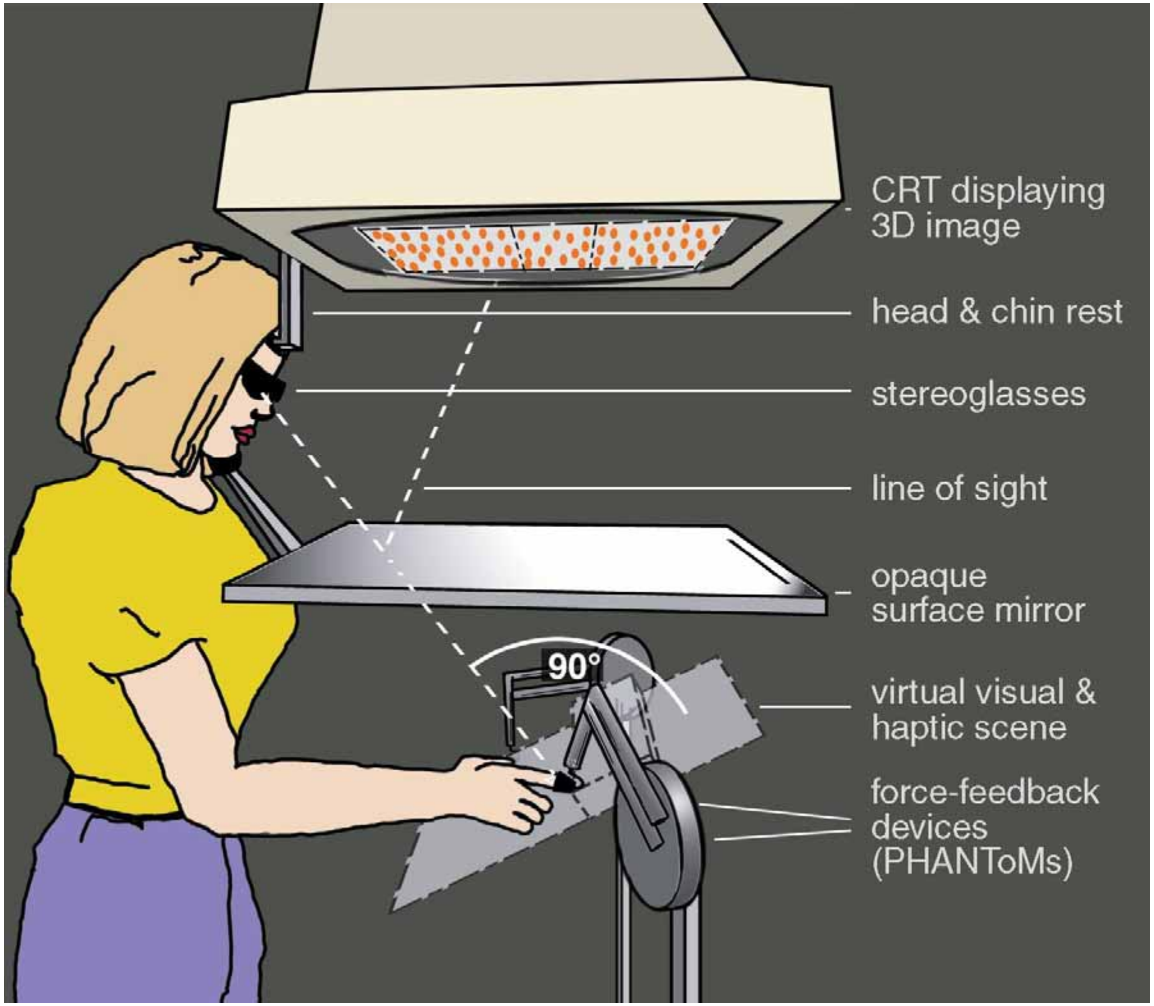
V 13.4	*H* 23.1	*V* *H* 14.1 mm	Vision alone 
V 14.1	*H* 20.5	*V* *H* 14.5 mm	Haptic alone 

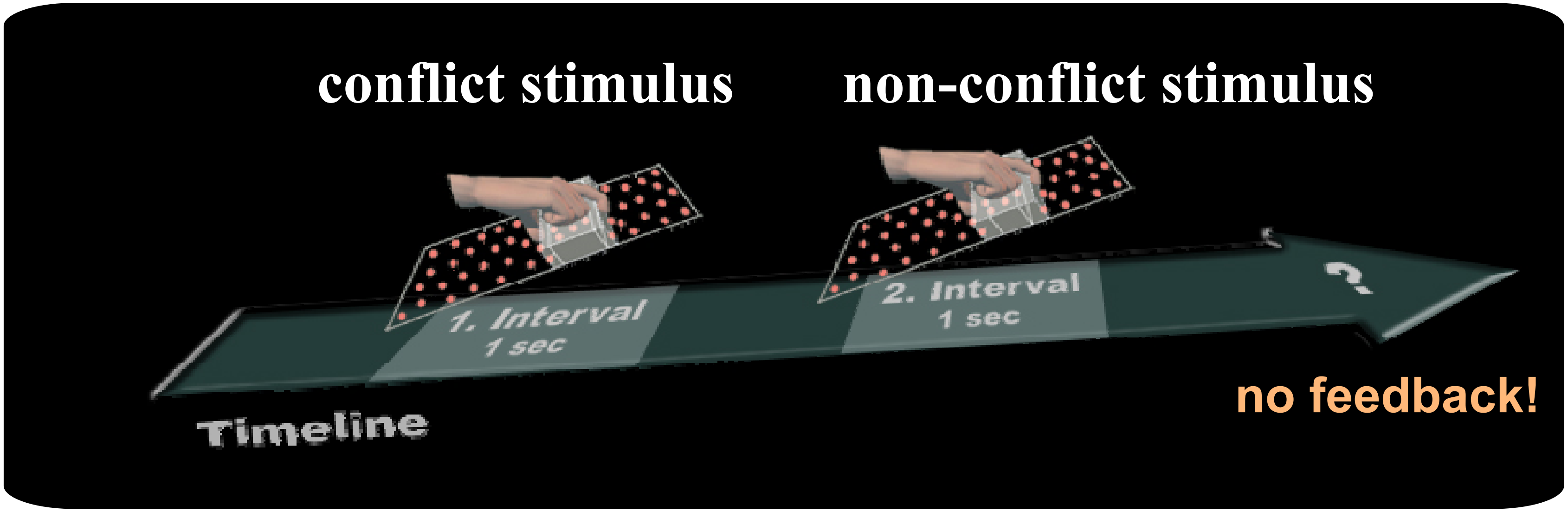
“Visual Capture”

Visual-Haptic Integration

Irv Rock revisited by Marc Ernst

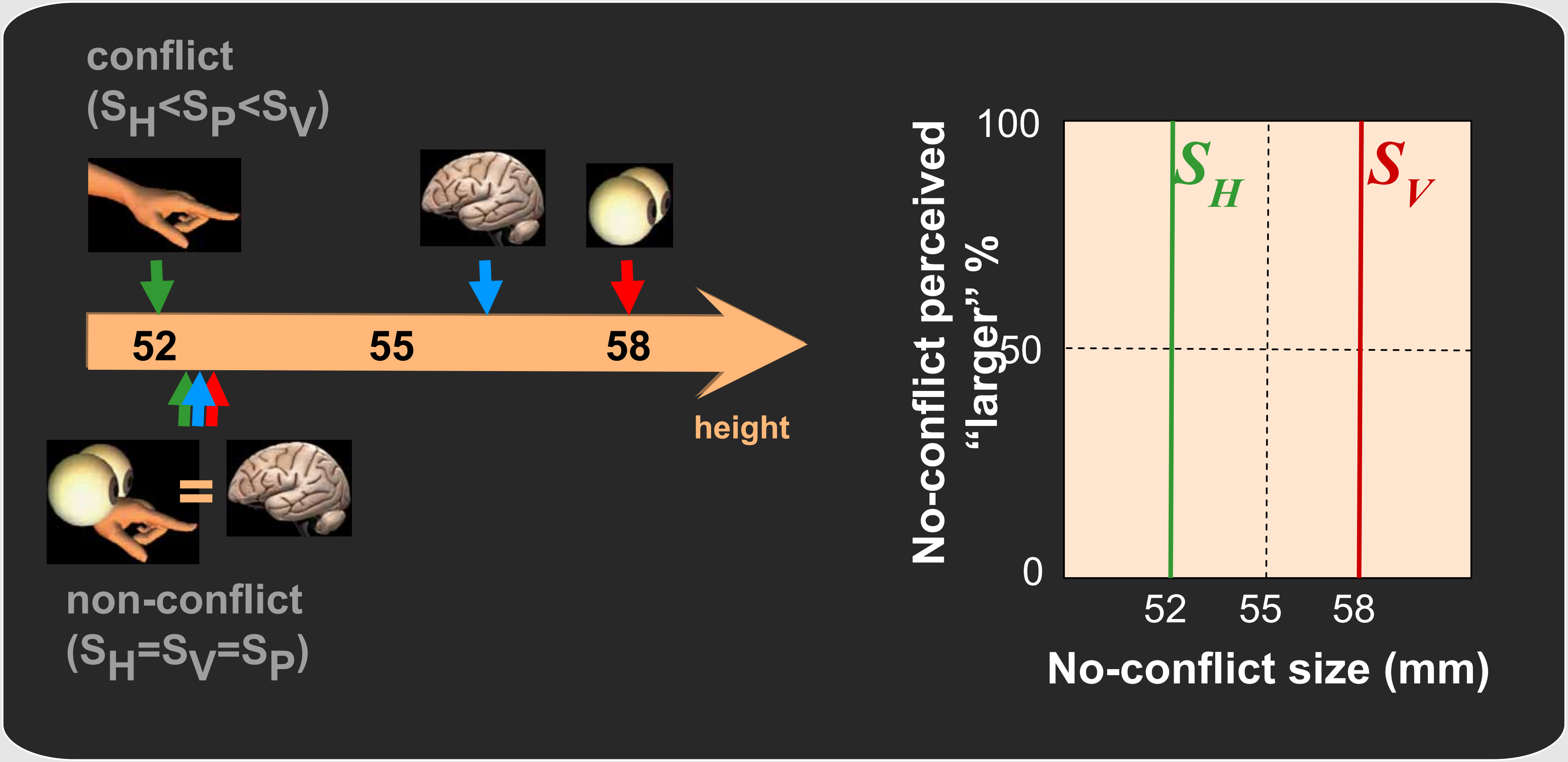


Size Comparison
with visual and haptic cues

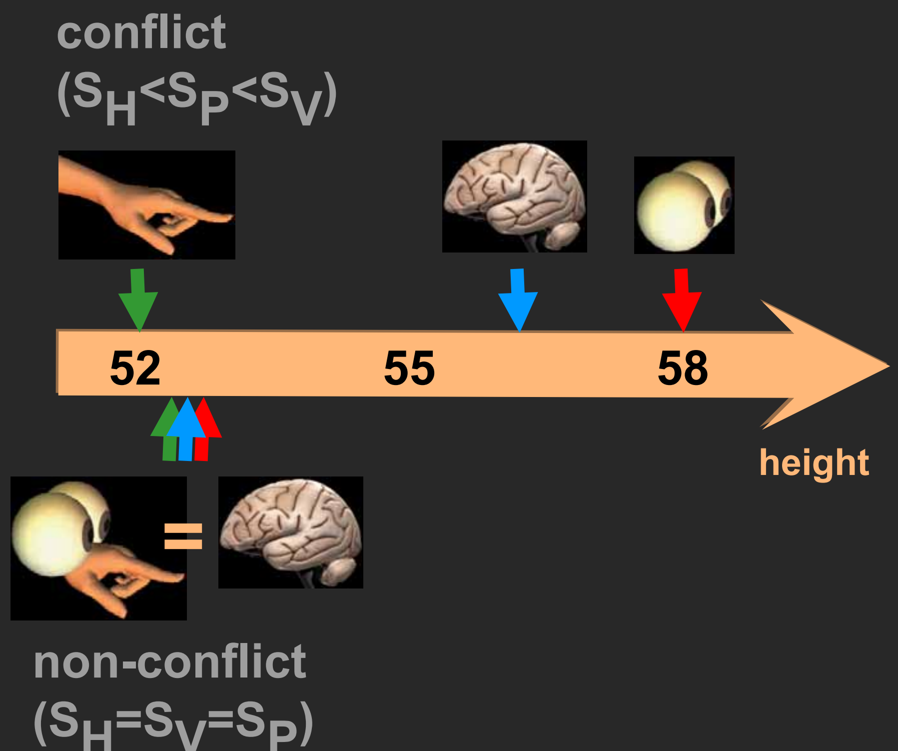


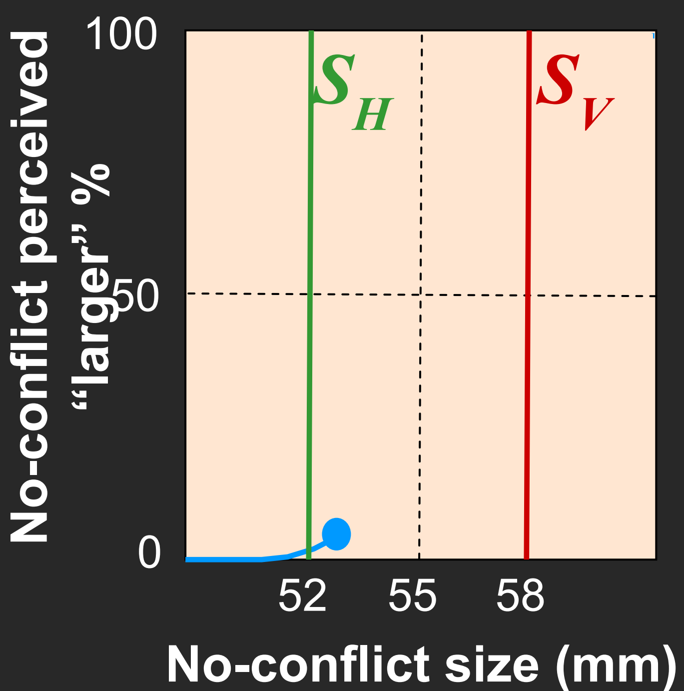
- Two Interval Forced Choice Task (2-IFC)
  - which one is bigger?
- which size do we need for the non-conflict stimulus
  to be perceptual the same size as the conflict stimulus?
- conflicts are below perceptual threshold

Combined Visual-Haptic Experiment

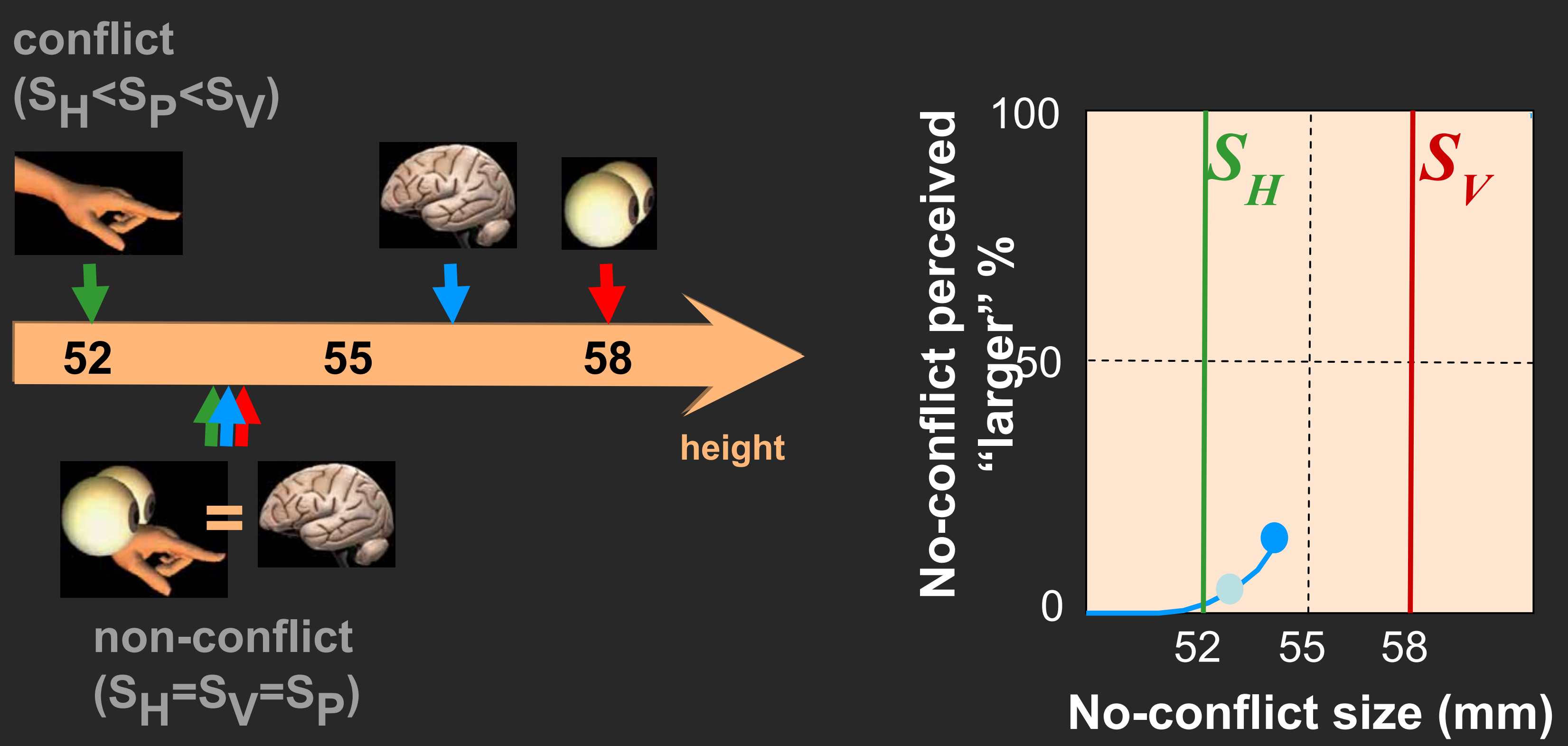


Combined Visual-Haptic Experiment





Combined Visual-Haptic Experiment



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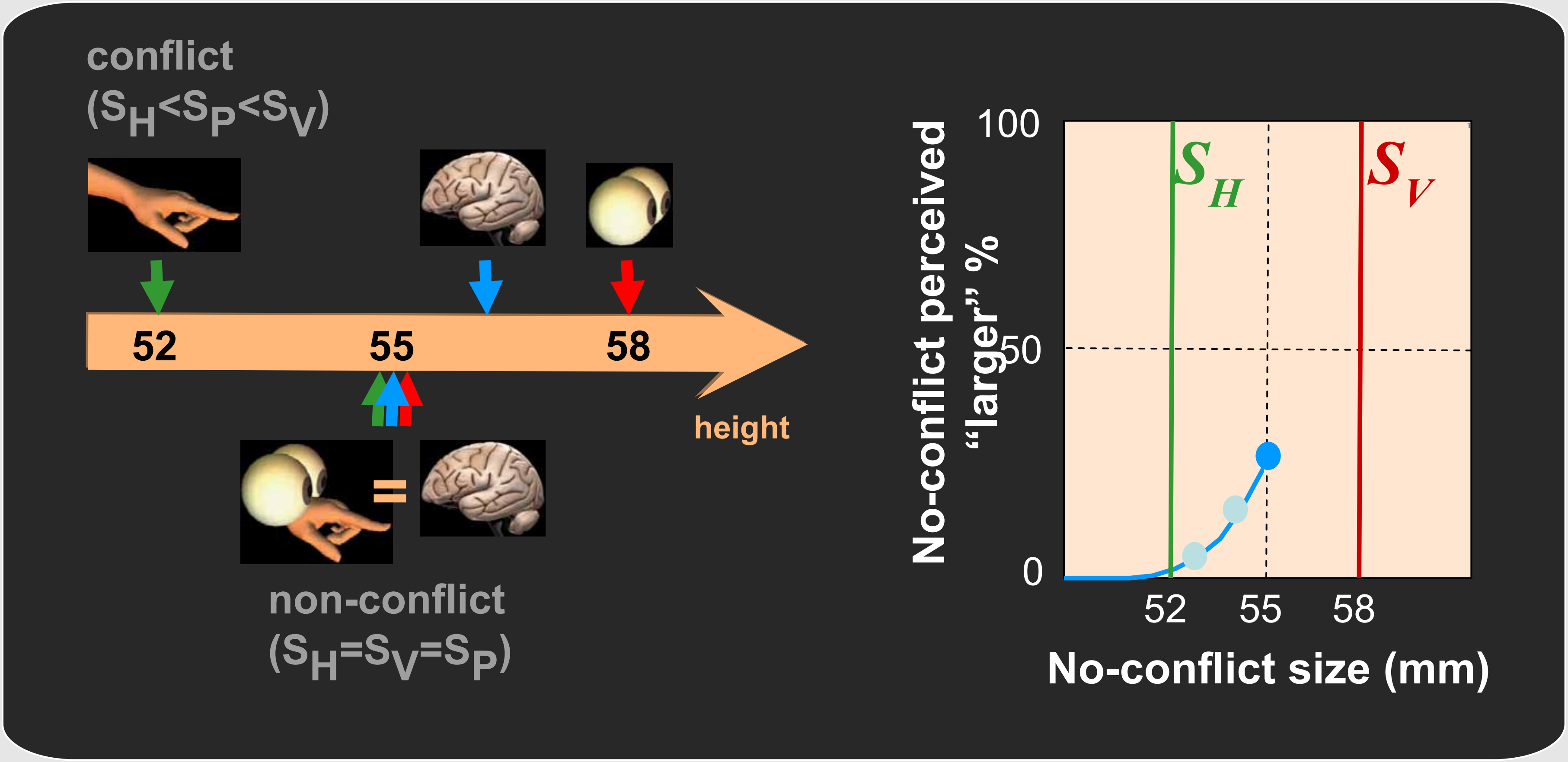
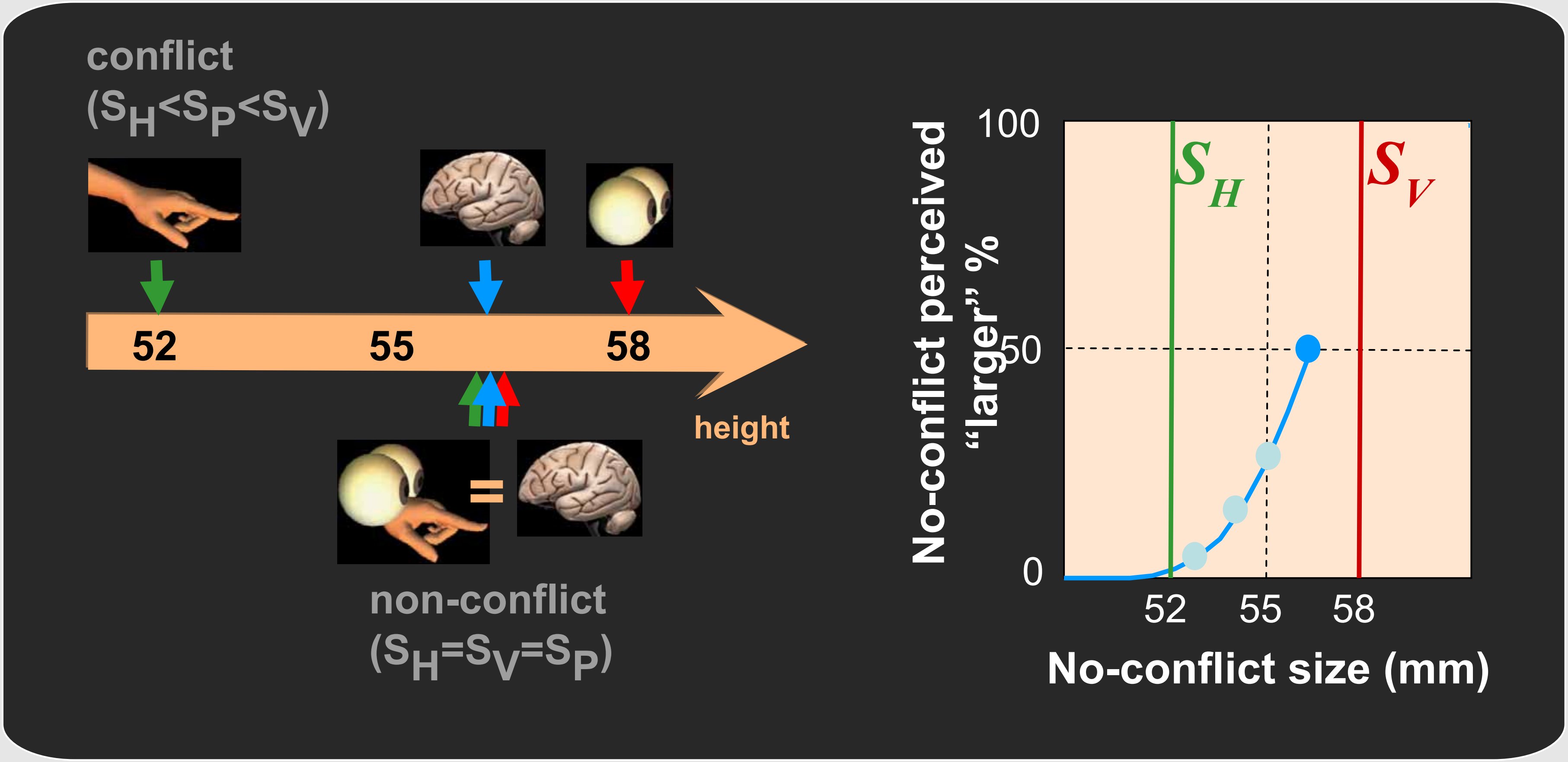


Combined Visual-Haptic Experiment



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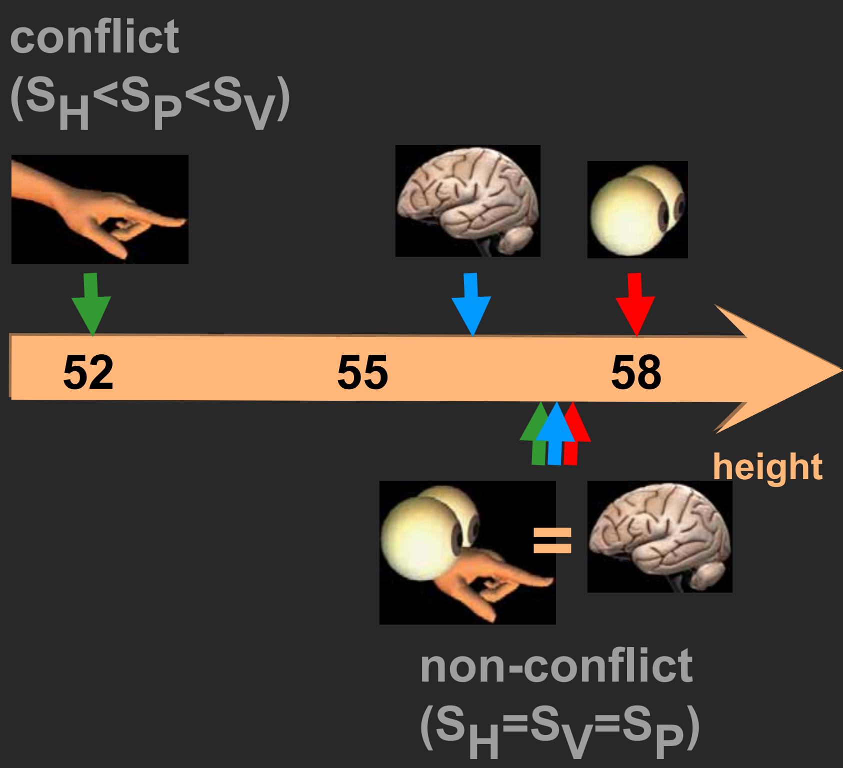

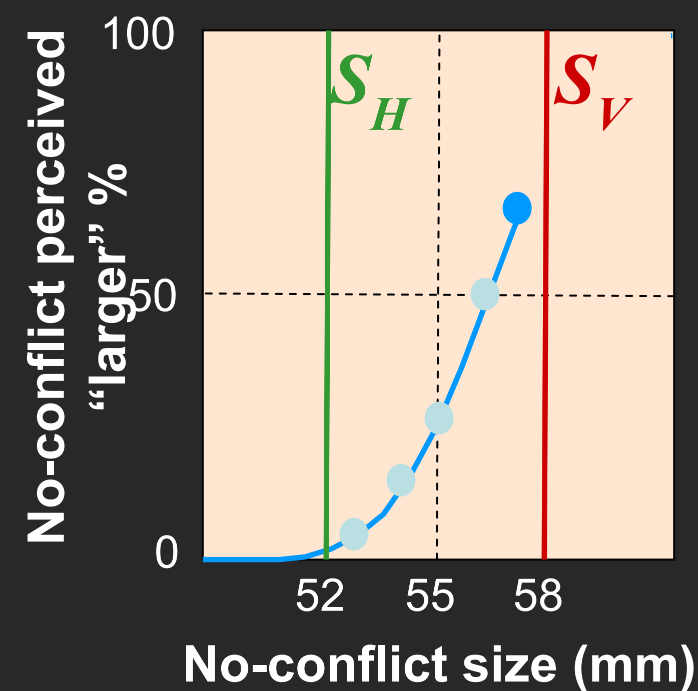

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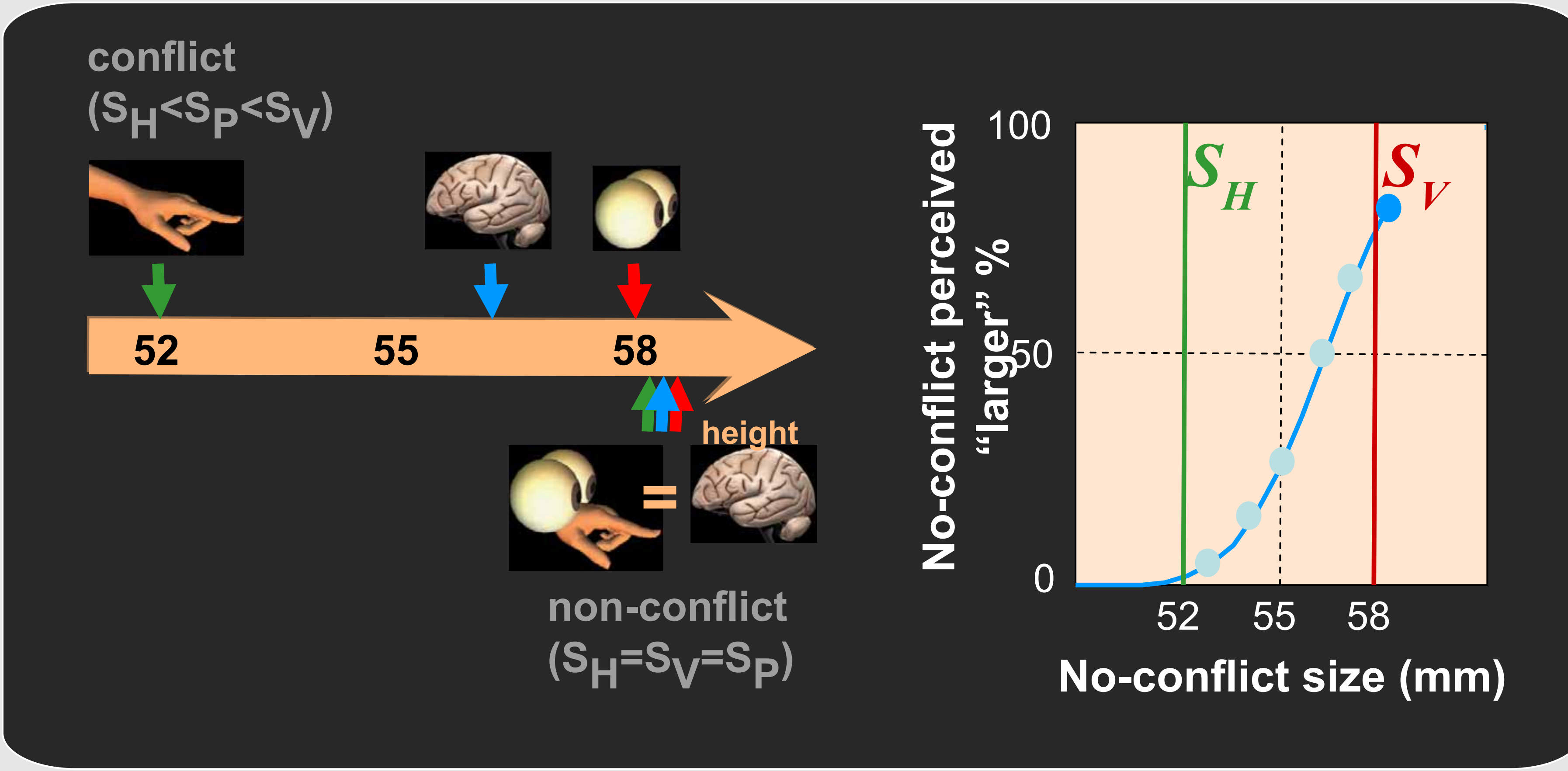
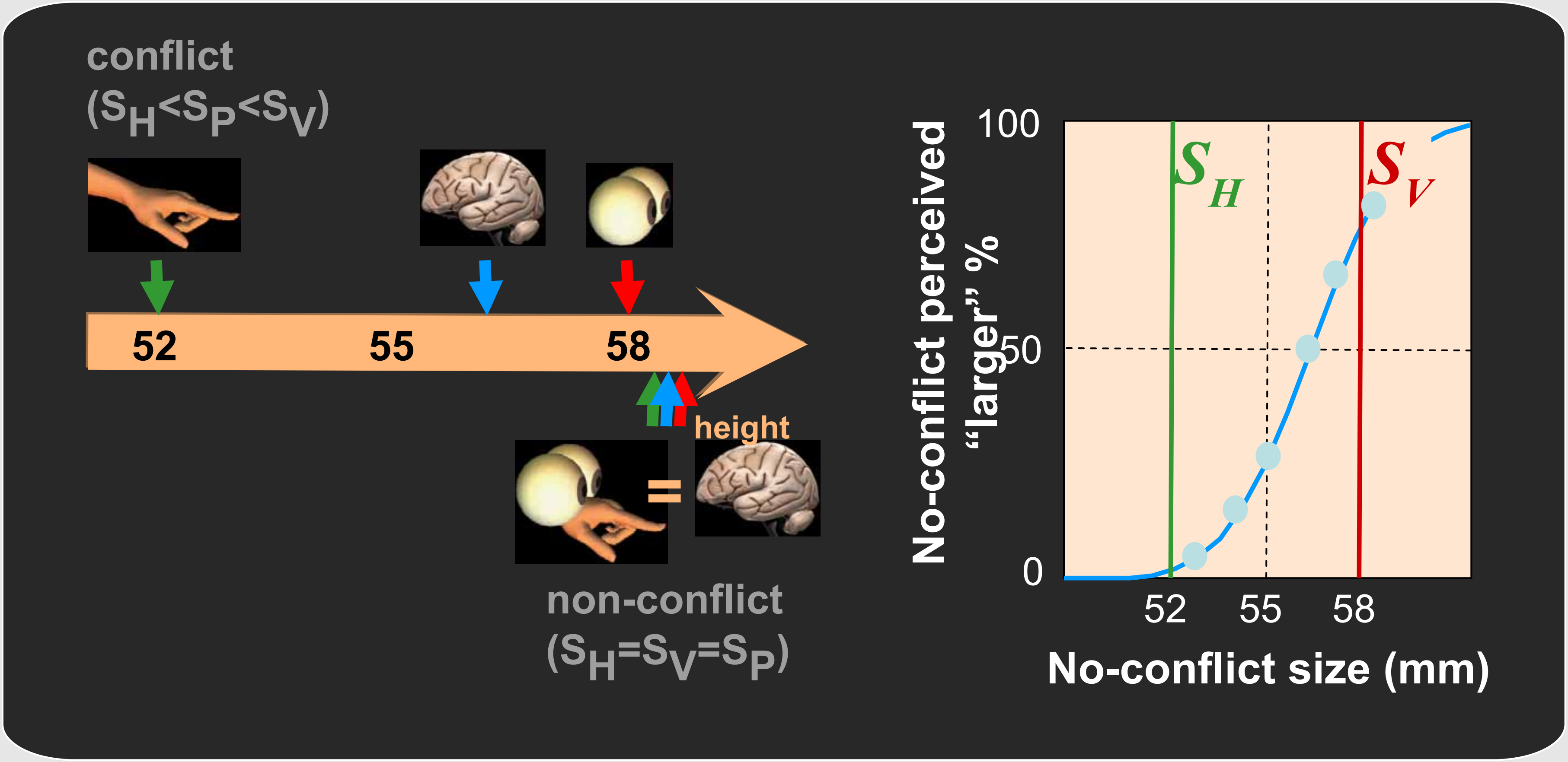
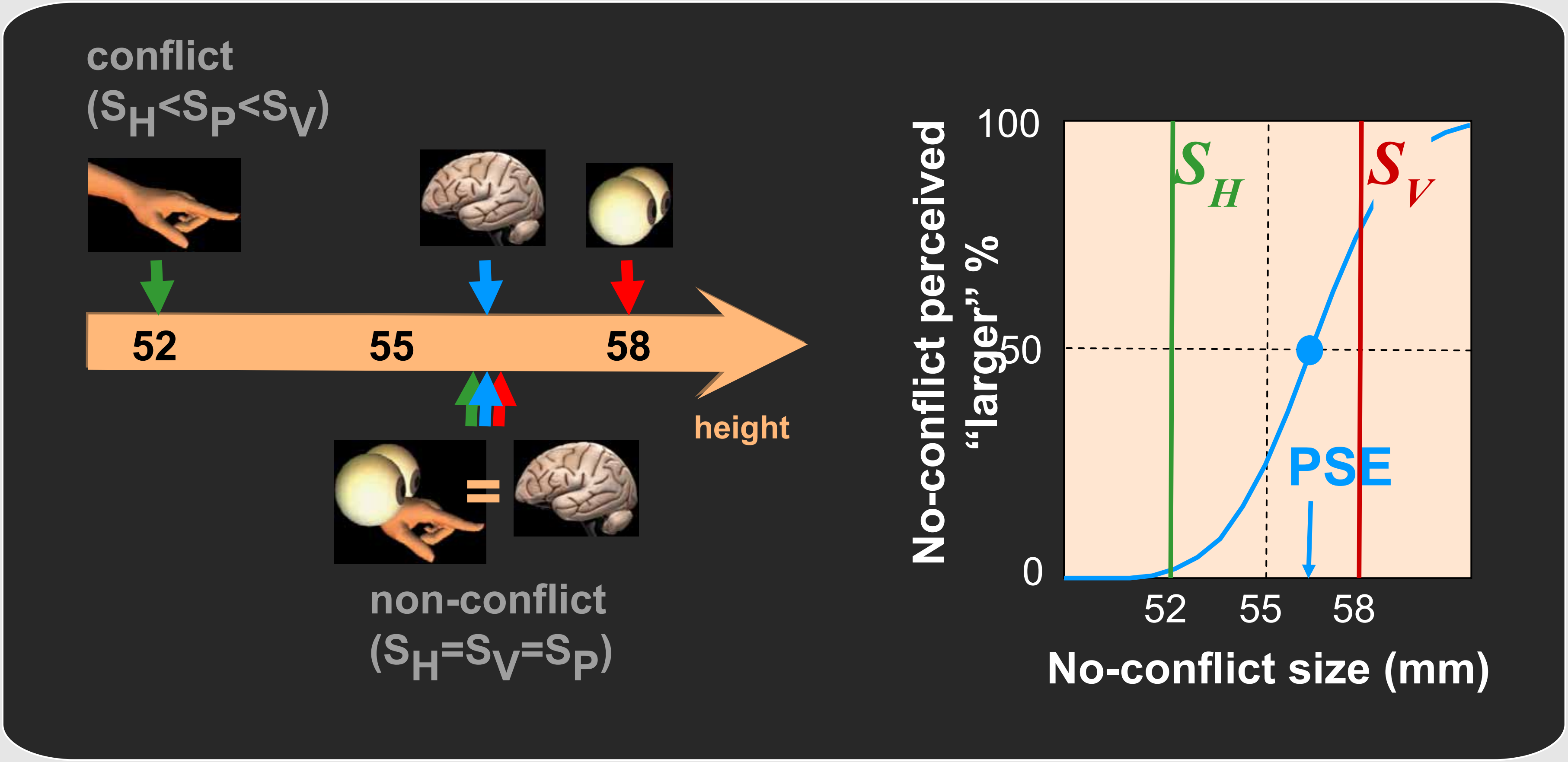


Combined Visual-Haptic Experiment



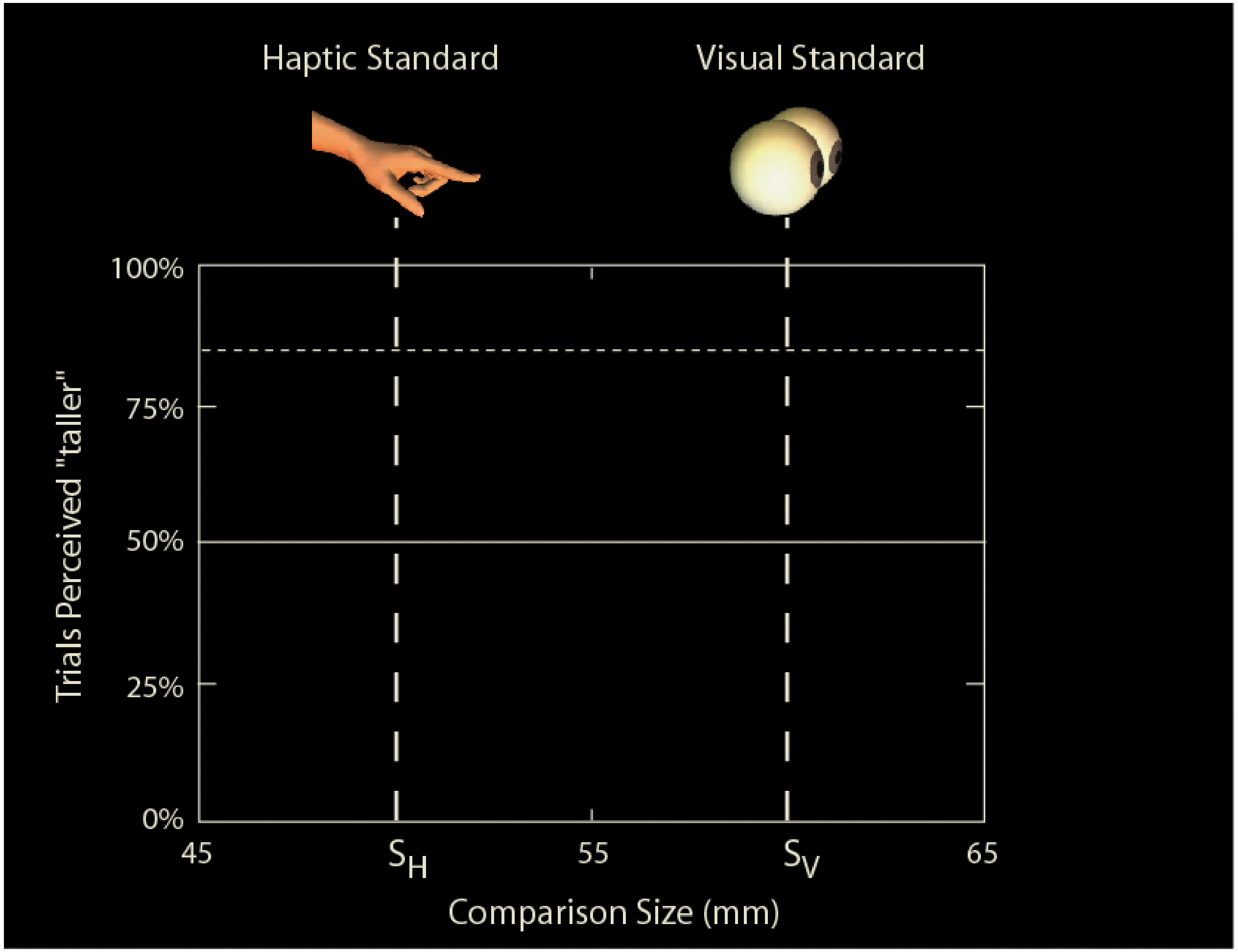
Combined Visual-Haptic Experiment



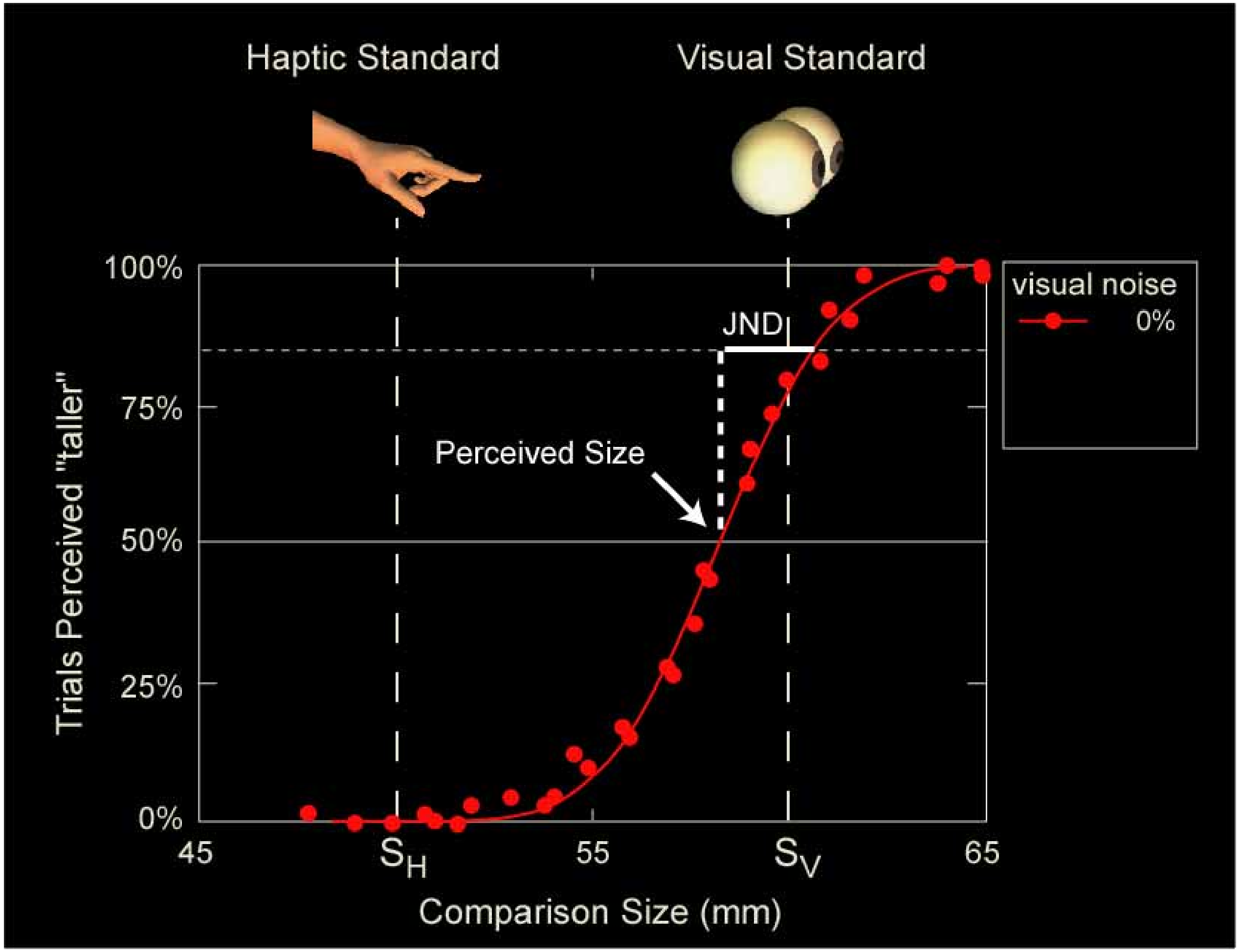
Point of subjective equality (PSE):

Value of no-conflict stimulus perceived as same size as conflict stimulus.

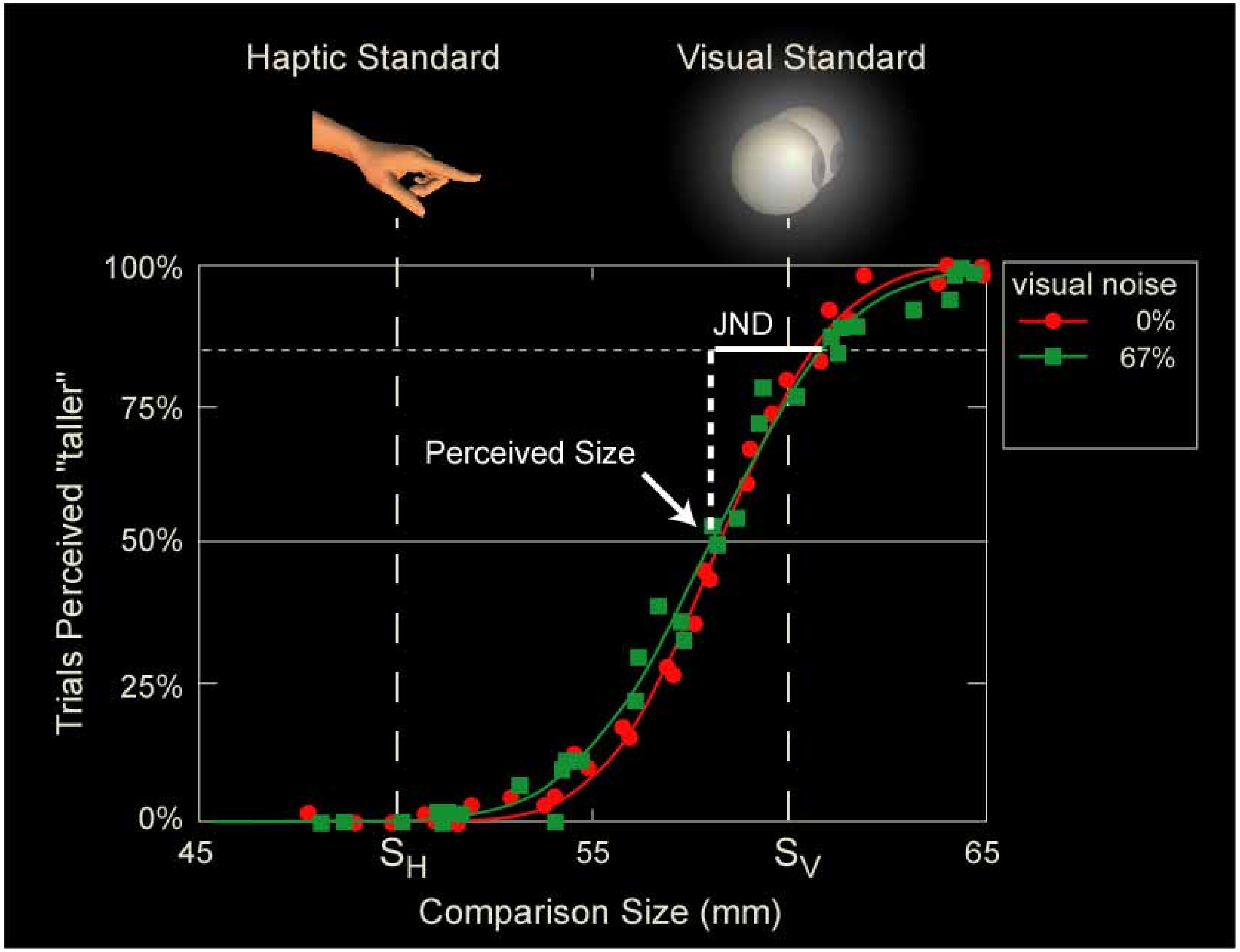
Visual-Haptic Integration



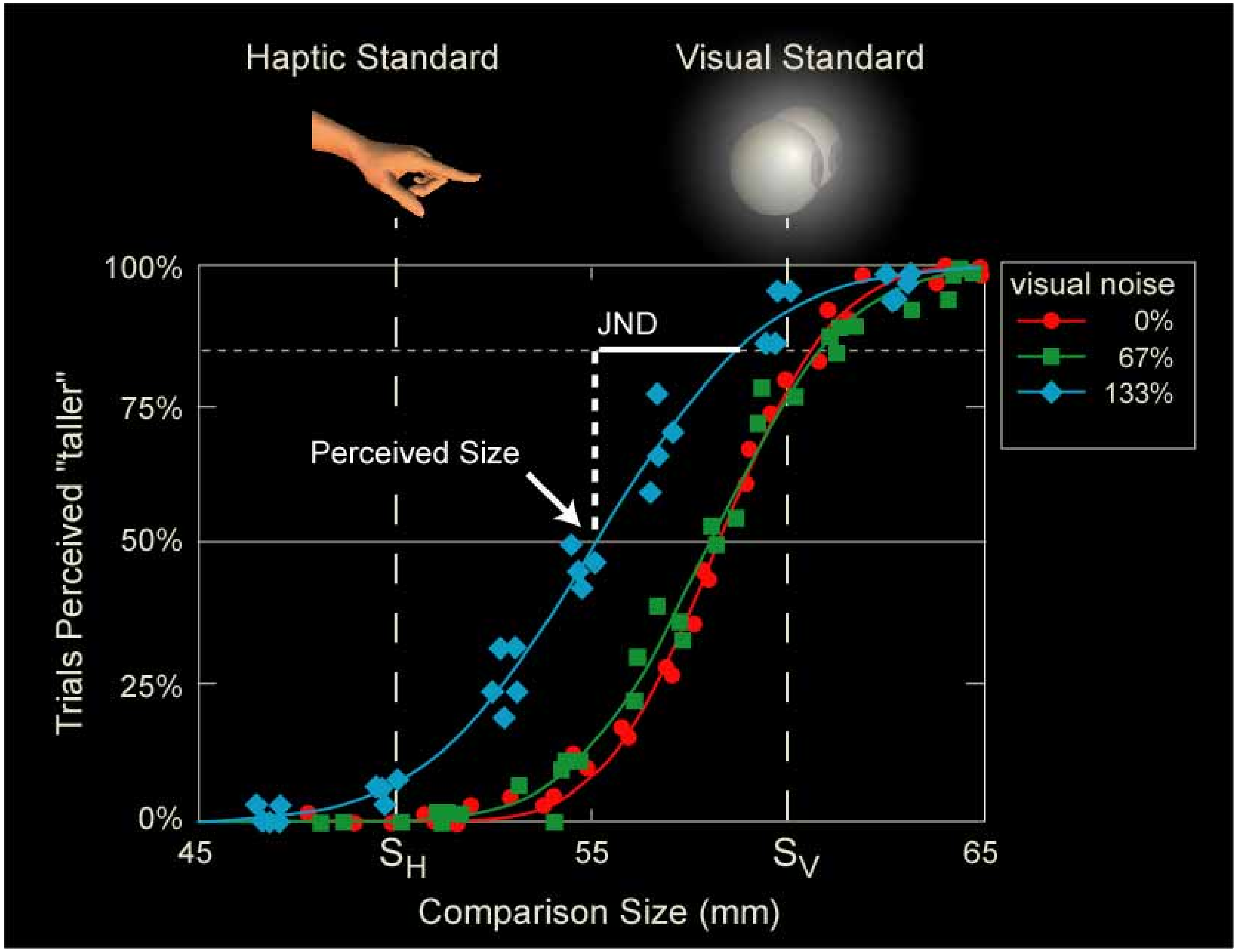
Visual-Haptic Integration



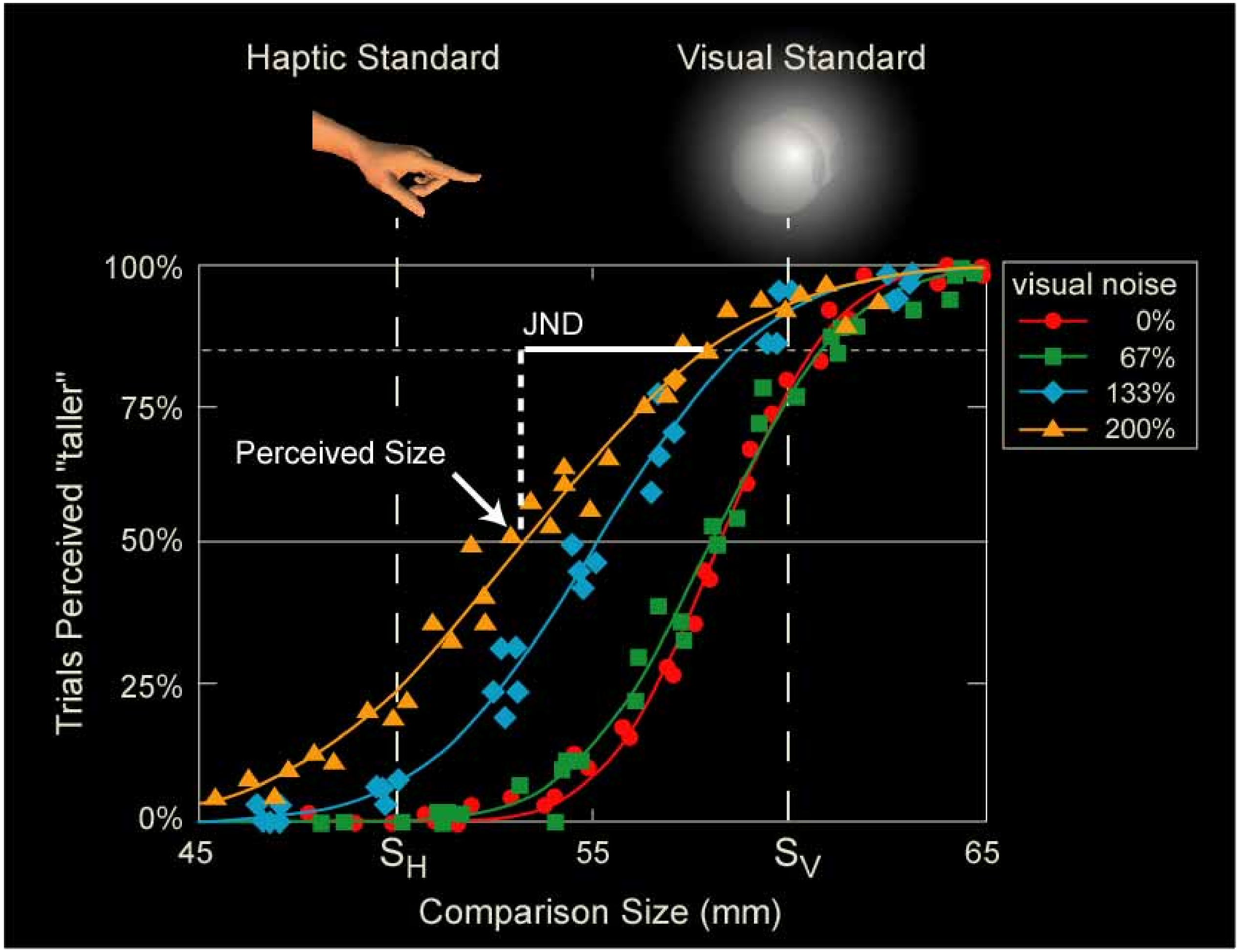
Visual-Haptic Integration



Visual-Haptic Integration



Visual-Haptic Integration

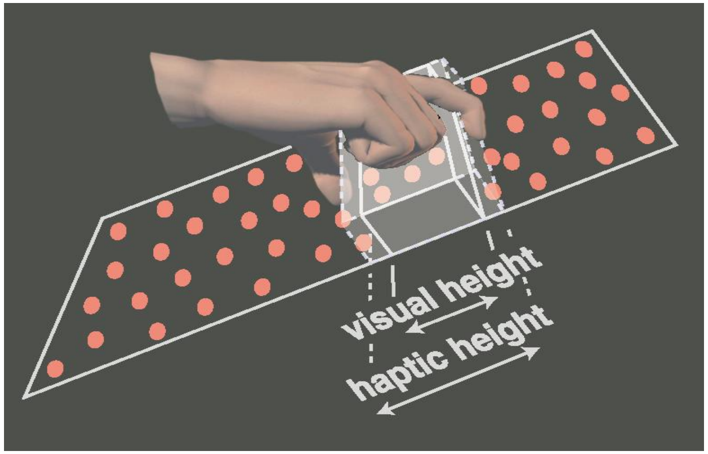


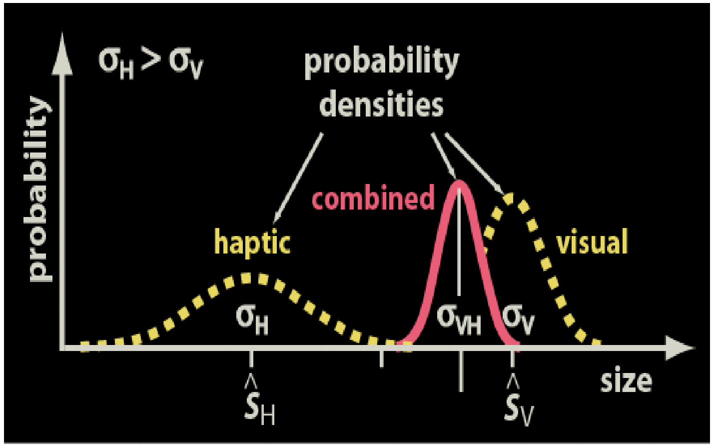
Summary
Visual-Haptic Integration

- the brain combines visual and haptic information in a statistically optimal way
  - Ernst, Banks & Bülthoff *Nature Neuroscience* 3 (1), 69-73 (2000)
  - Ernst & Banks *Nature* 415, 429-433 (2002)
  - Hillis, Ernst, Banks & Landy *Science* 298, 1627-1630 (2002)
  - Ernst & Bülthoff, *TICS* 8, 162-169 (2004)
- cues are weighted according to their reliability (variance)

$$\hat{S}_{VH} = w_V \hat{S}_V + w_H \hat{S}_H$$

- combination reduces variance
- explains "visual capture"
  - **the variance of visual size estimates is much smaller than haptic estimate**
  - **visual weight set to ~ 1.0**





Visual-Auditory Integration

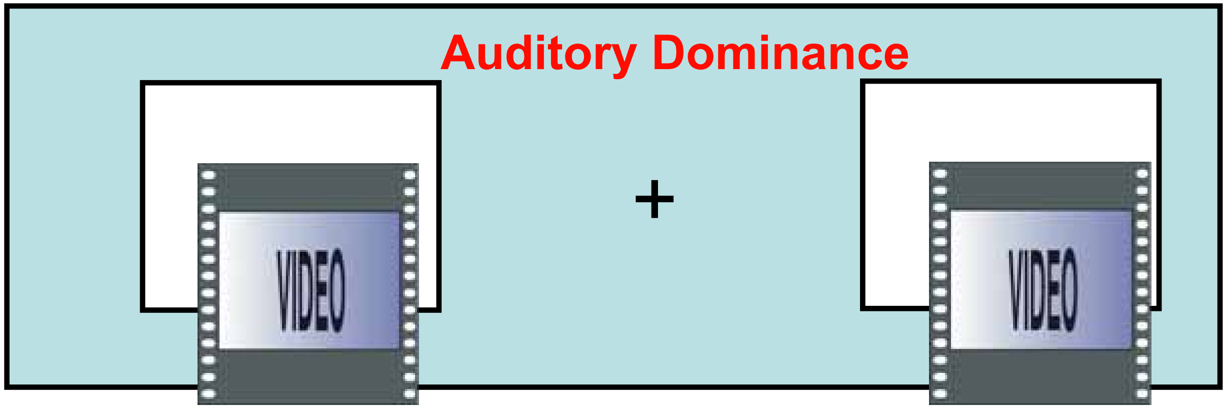
- Visual-Auditory Localization: Ventriloquist effect

Visual Dominance

The ventriloquist effect results from near-optimal bimodal integration
D. Alais & D. Burr, Curr. Biol. 2004

Edgar Bergen & Charlie McCarthy

- Visual-Auditory Temporal Judgments



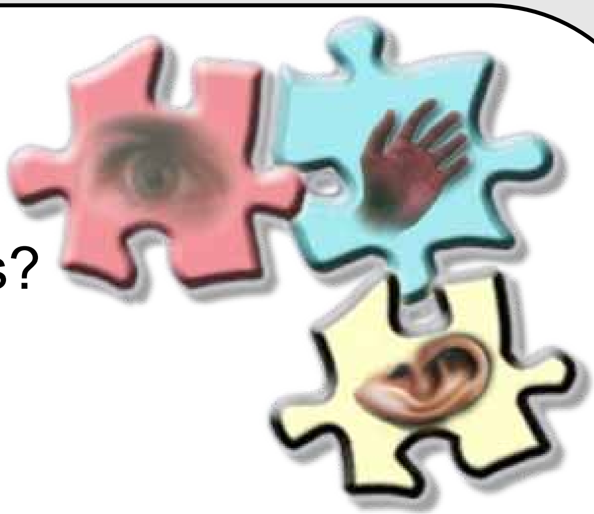
What you see is what you hear.
L. Shams, Y. Kamitani & S. Shimojo, Nature 2000

What you see is what you hear

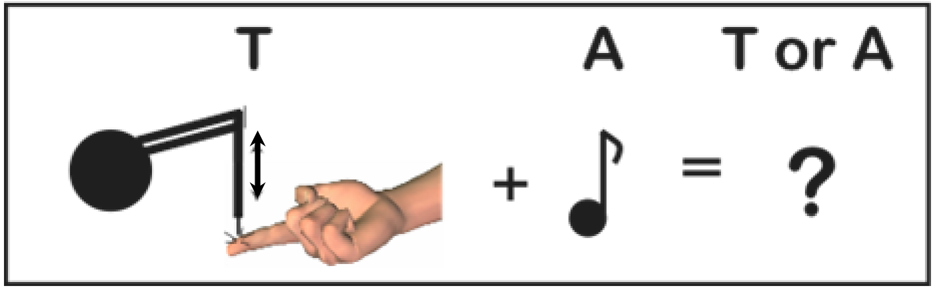
1

2

Integration of Temporal Events

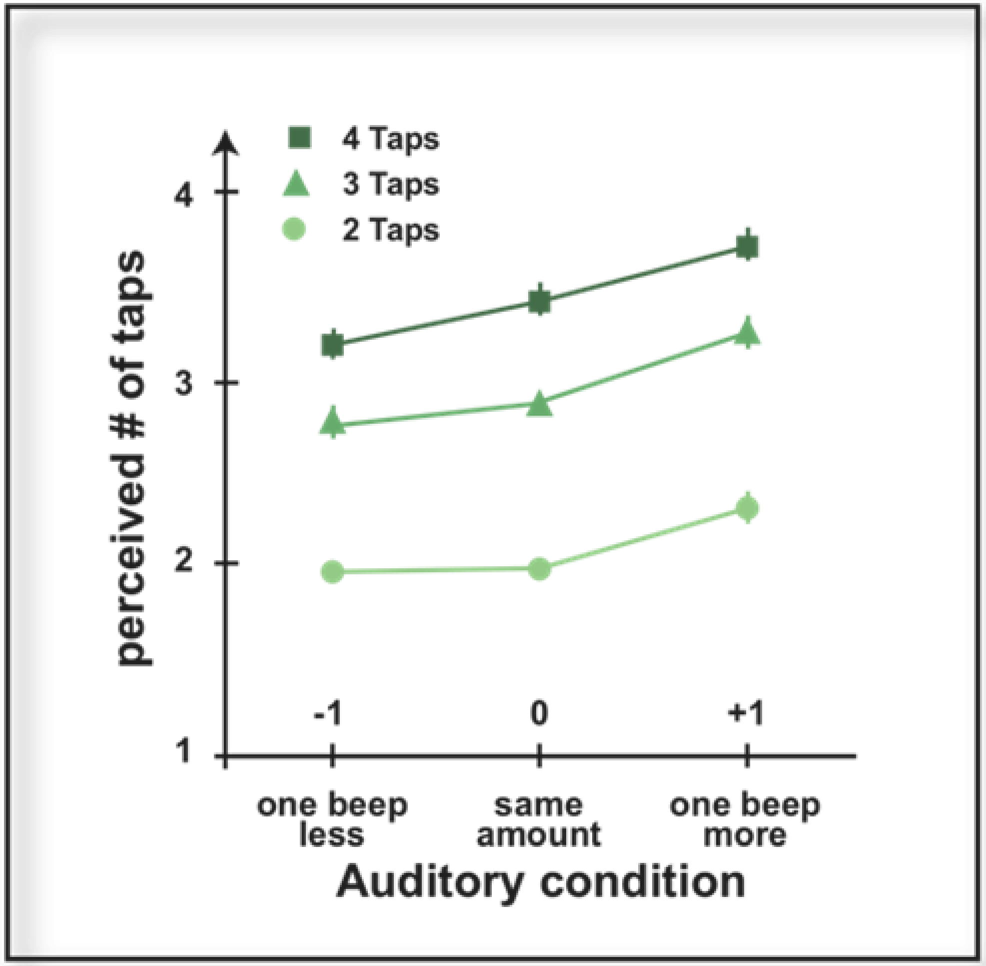


Is the **integration of temporal events** based on the **reliability of the signals**, similar to the integration of spatial signals?

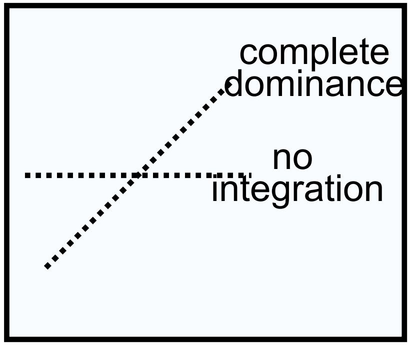


Instead of using vision and audition Ernst and Bresciani used **touch and audition**, because they are likely to be more comparable in terms of their reliabilities in processing temporal events.

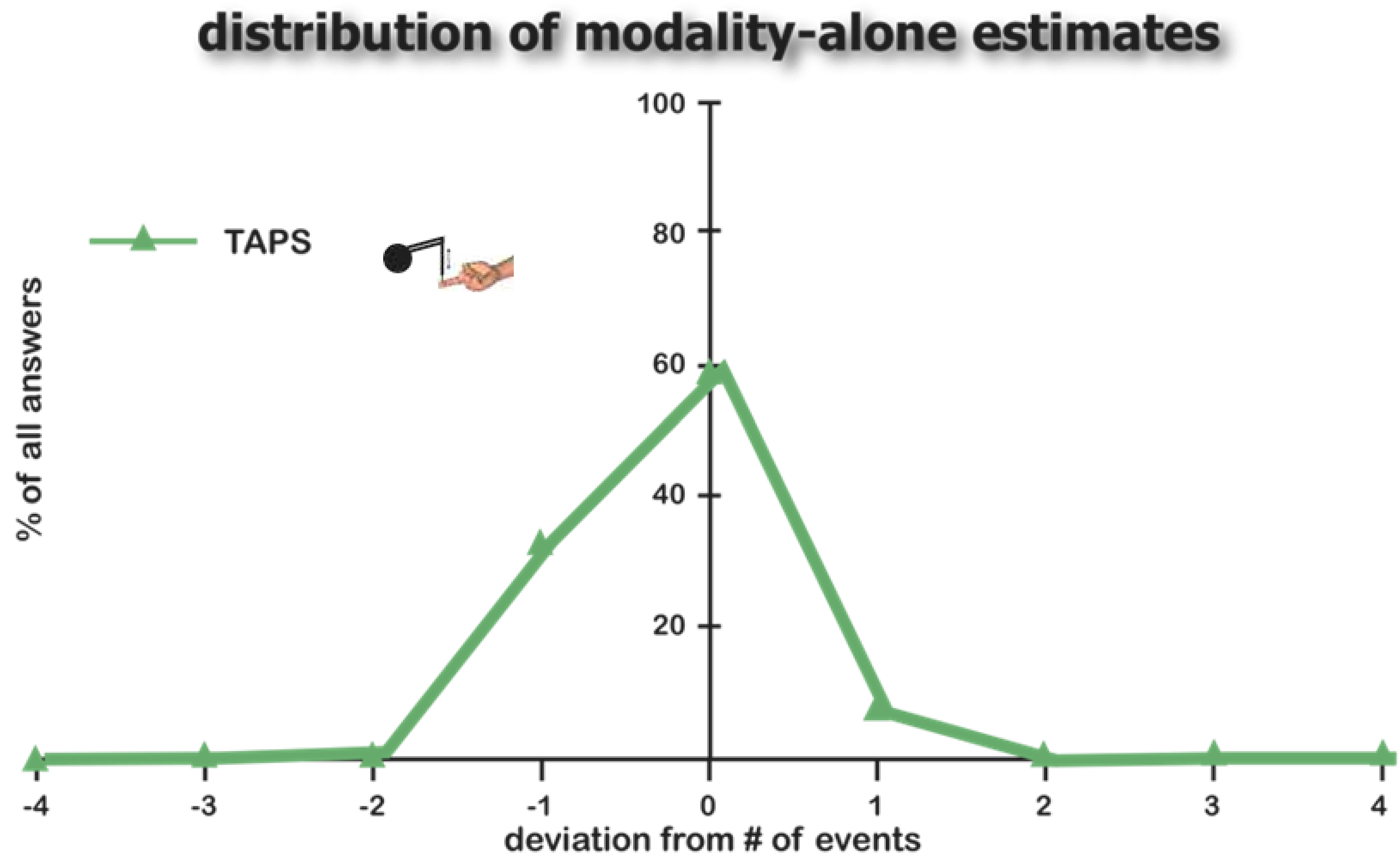
Auditory-Haptic Integration



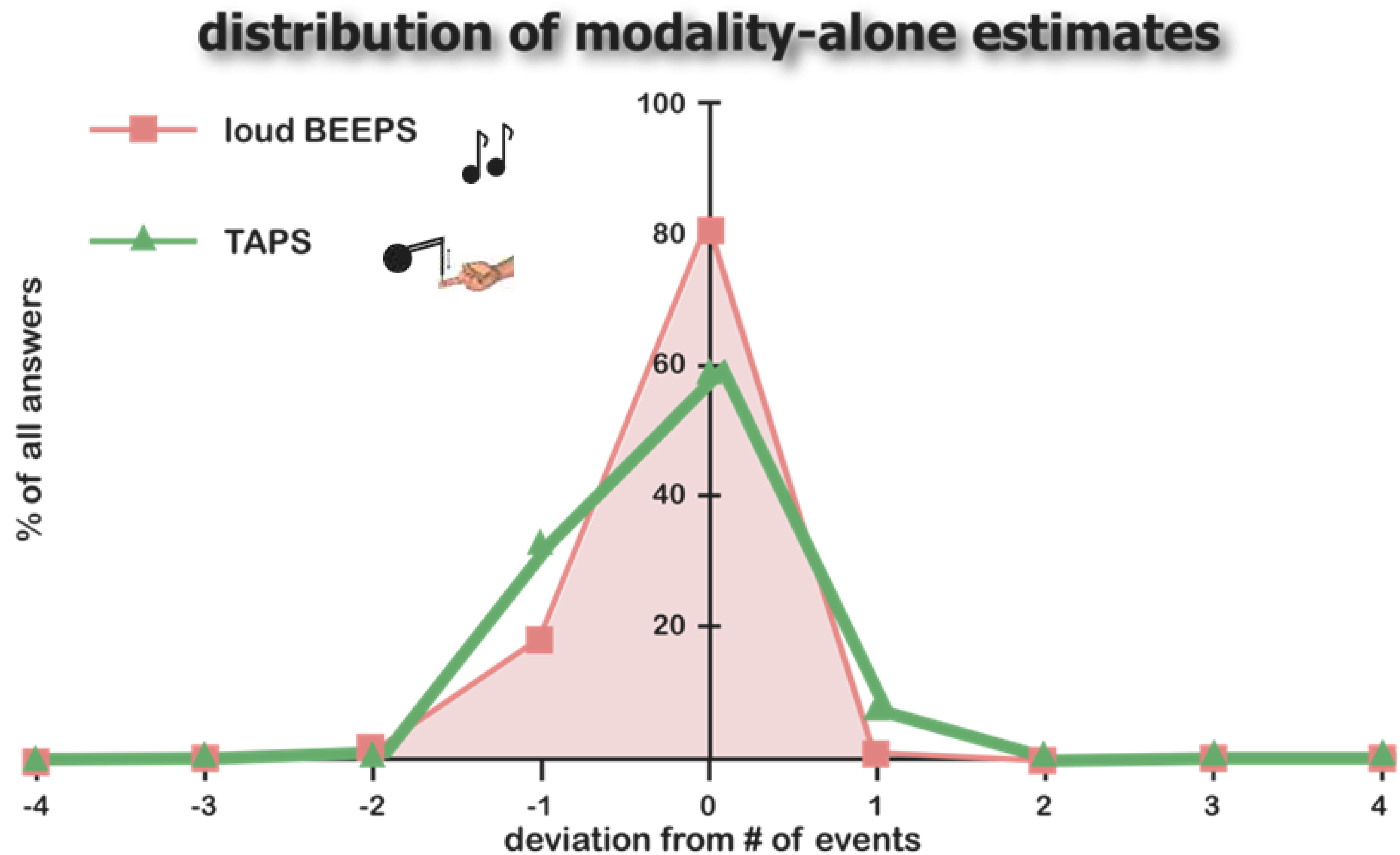
Predictions



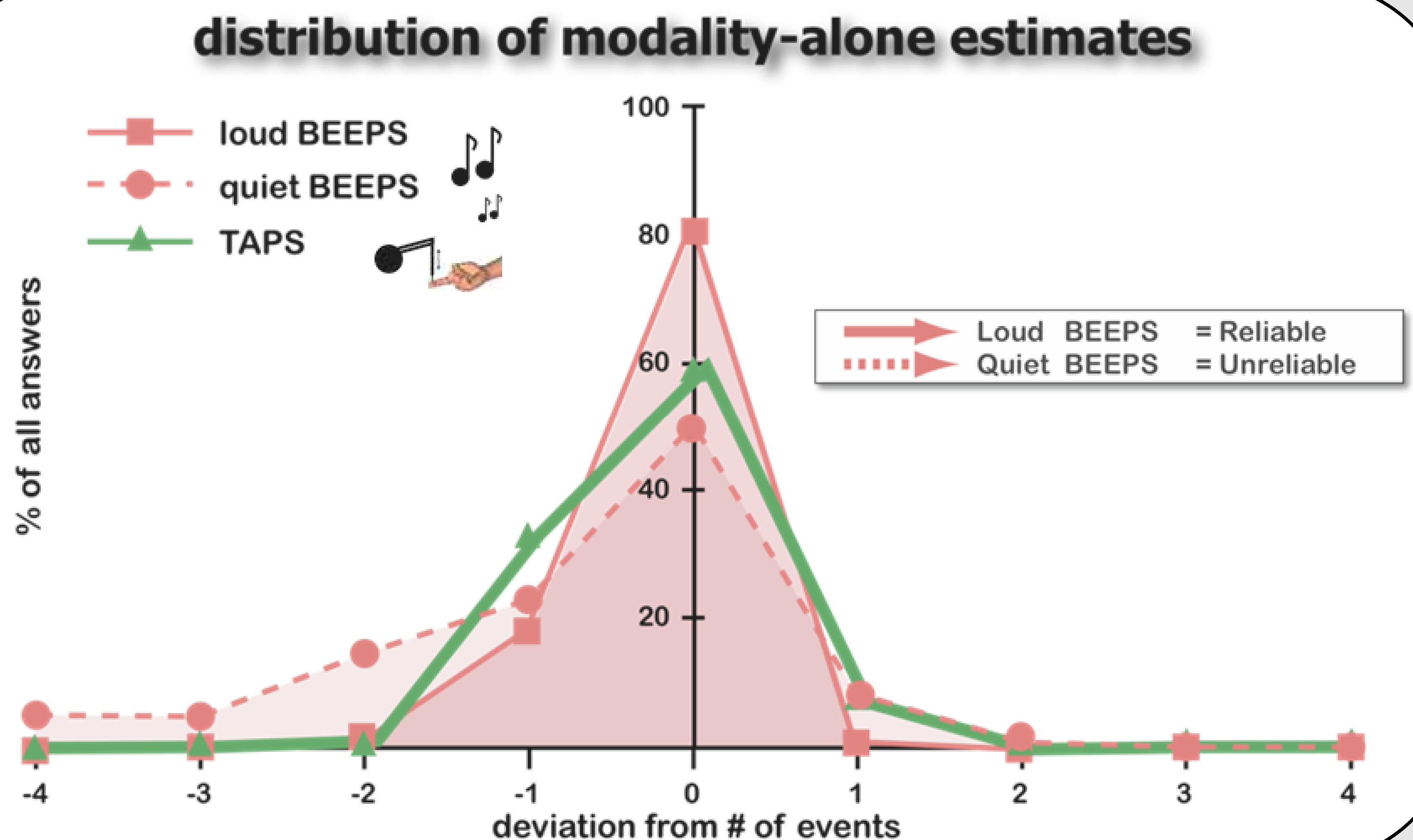
Signal Reliability



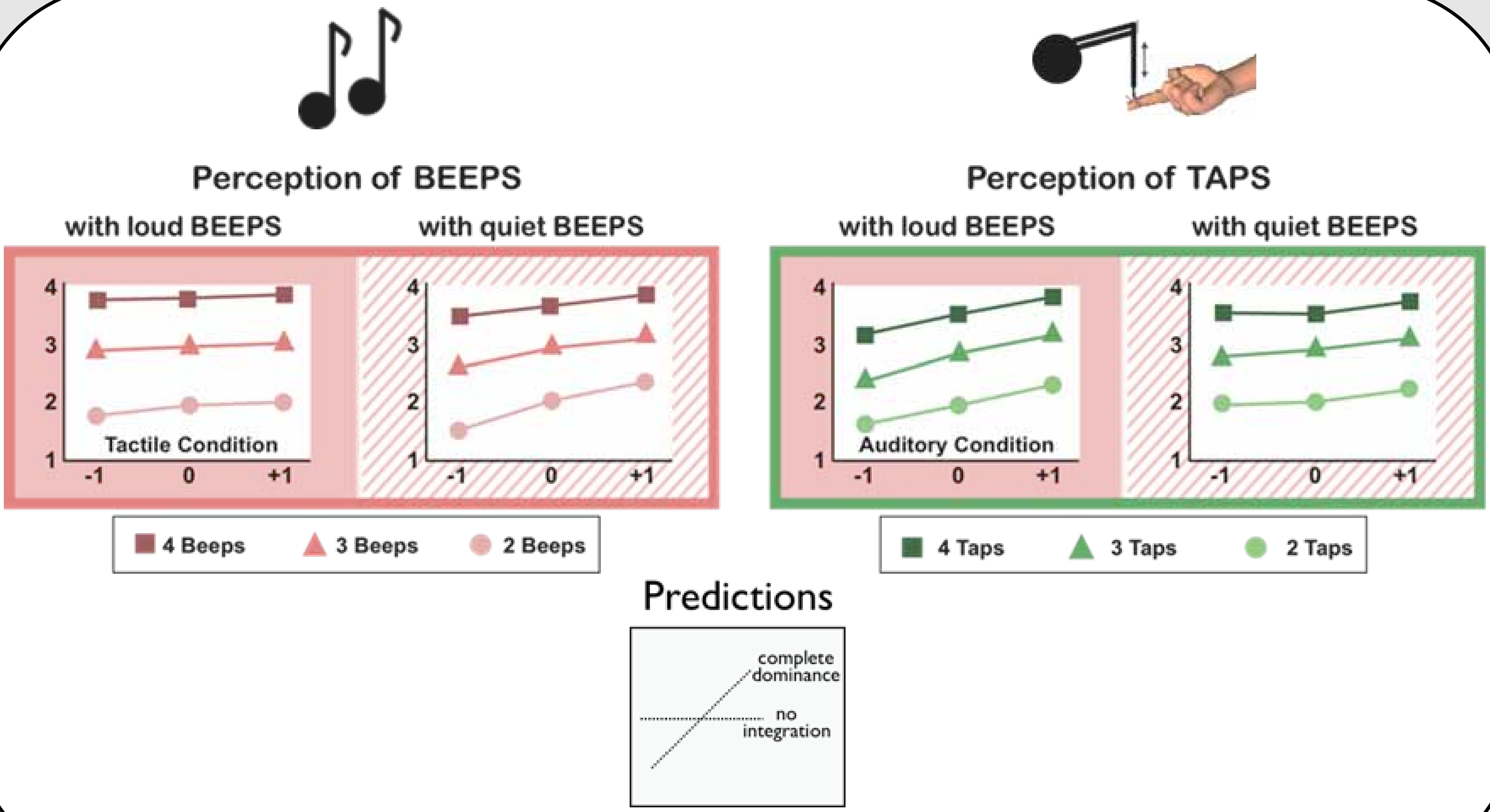
Signal Reliability



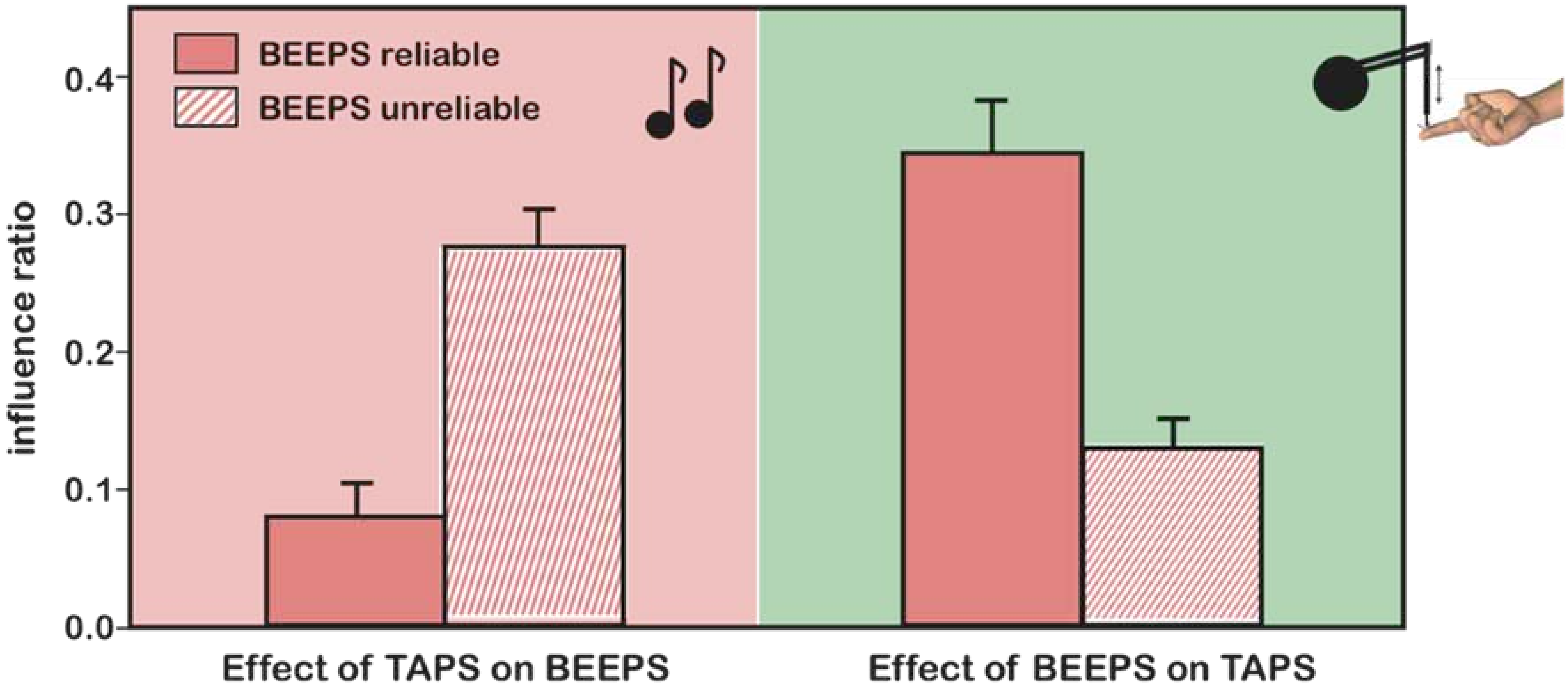
Signal Reliability



Effect of Reliability on Integration



Effect of Reliability on Integration

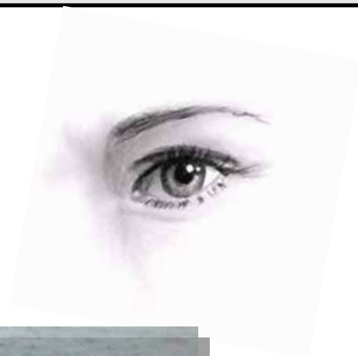


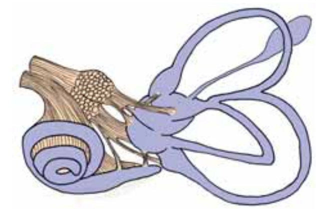
Conclusion: Integration of Temporal Events

- Tactile-auditory integration for sequences of temporal events
- The reliability of the signals determines the strength of bias

Marc Ernst Jean-Pierre Bresciani Abderrahmane Kheddarr
MPI Tübingen LSC Paris

Visual-Vestibular Integration

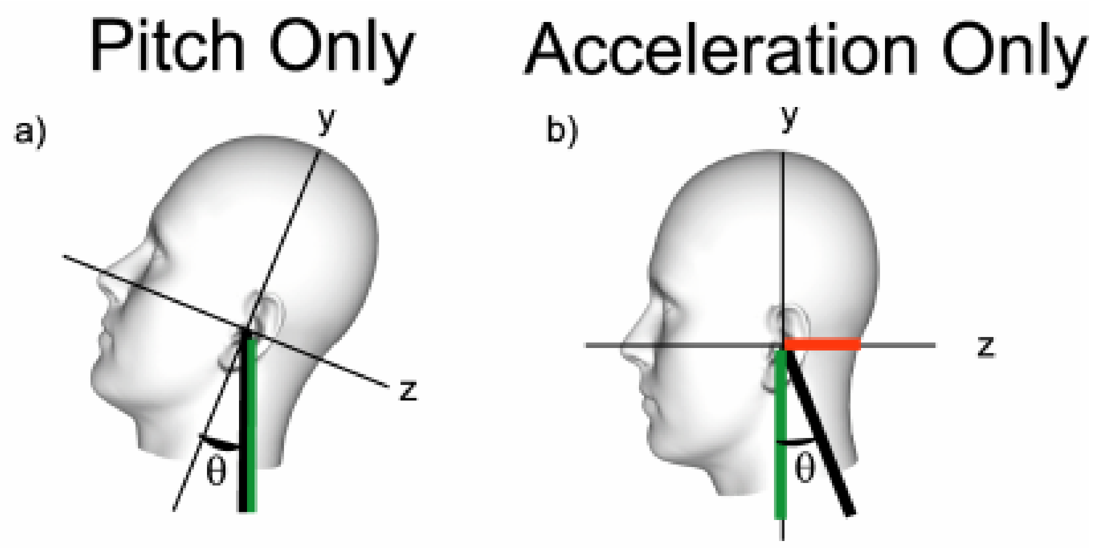




strong acceleration + low visibility

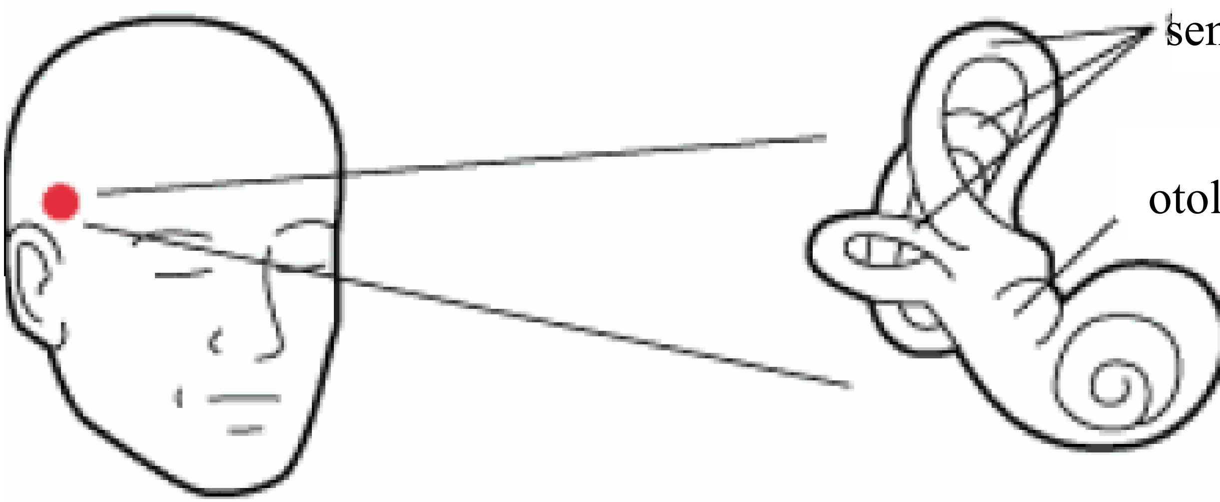
somatogravic illusion

Somatogravic Flight Illusion



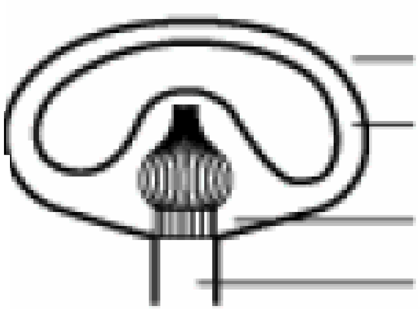
- Einstein:
  no sensor can distinguish gravity from translational acceleration.
- This holds of course for our otolith organs too
  - they sense gravity *minus* acceleration
  - they cannot distinguish certain tilts and motions

Vestibular System

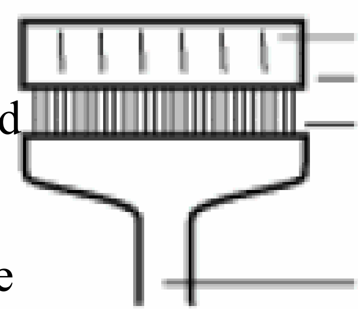


from Greek:
otos - ear
lithos - stone

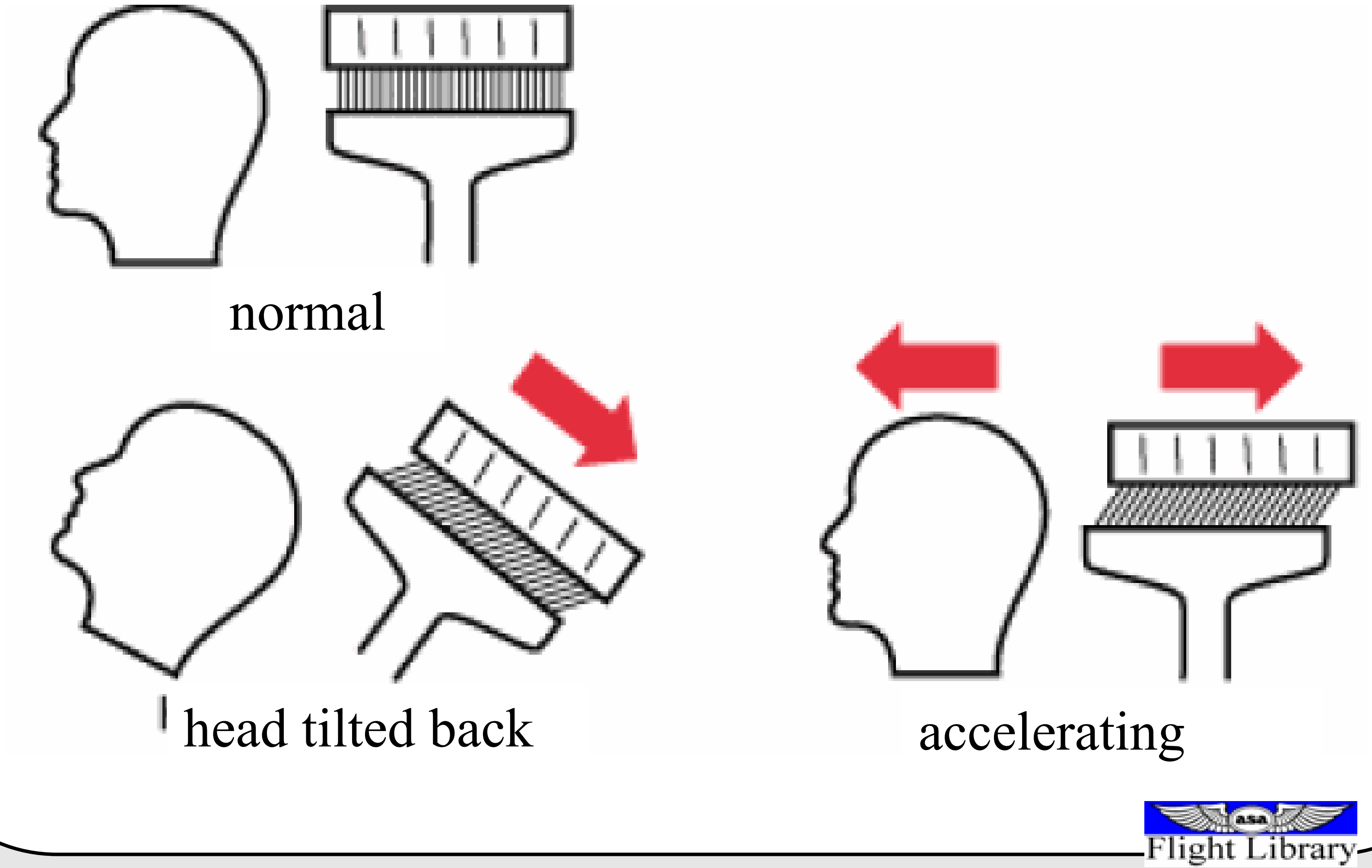
semicircular canal



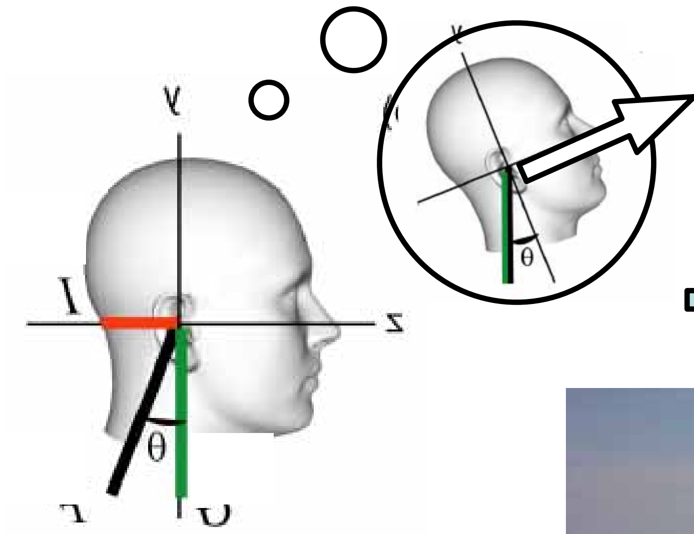
otolith organ



Otolithic System



Consequence
of somatogravic illusion



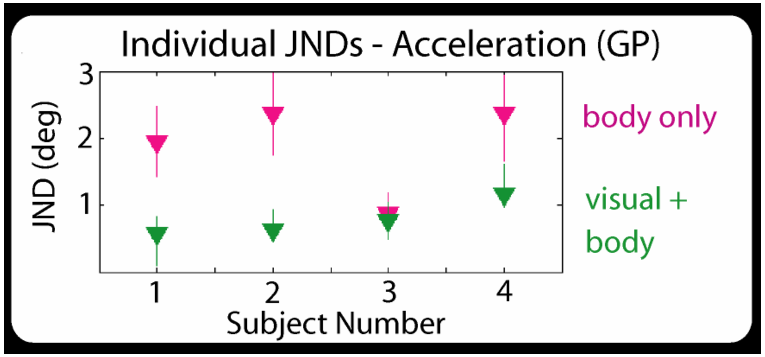
Consequence

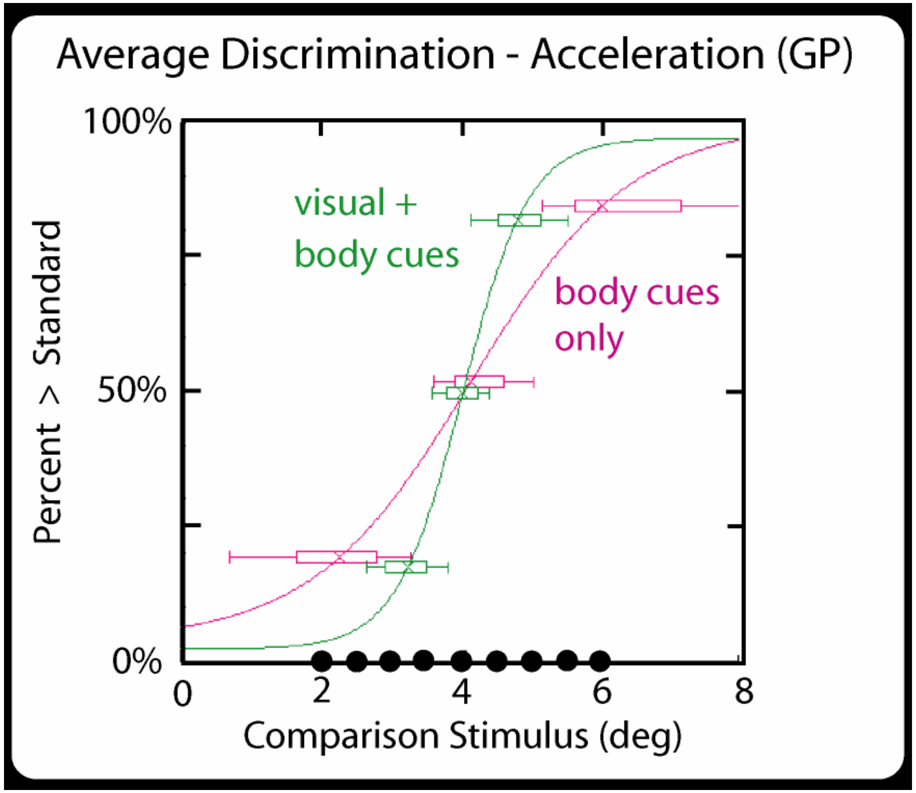
Pogen MacNeilage,
Daniel Berger,
Marty Banks,
Heinrich Bülthoff

Multimodal Integration: visual – body cues

MacNeilage, Berger, Banks & Bülthoff, VSS 2004

- Which cues are best to override the **strong but wrong cues** from the vestibular system?
- Examine influence of **visual** forward-movement on **perceived tilt** during real tilt





Implications for Cockpit Design

- artificial horizons are not always sufficient to overcome the somatogravic illusion
- we need an attitude indicator which overrides the somatogravic illusion
- **visual and auditory capture**
  might be the answer how to improve
  flight safety in low visibility conditions

High-Level Integration

Attention and Awareness

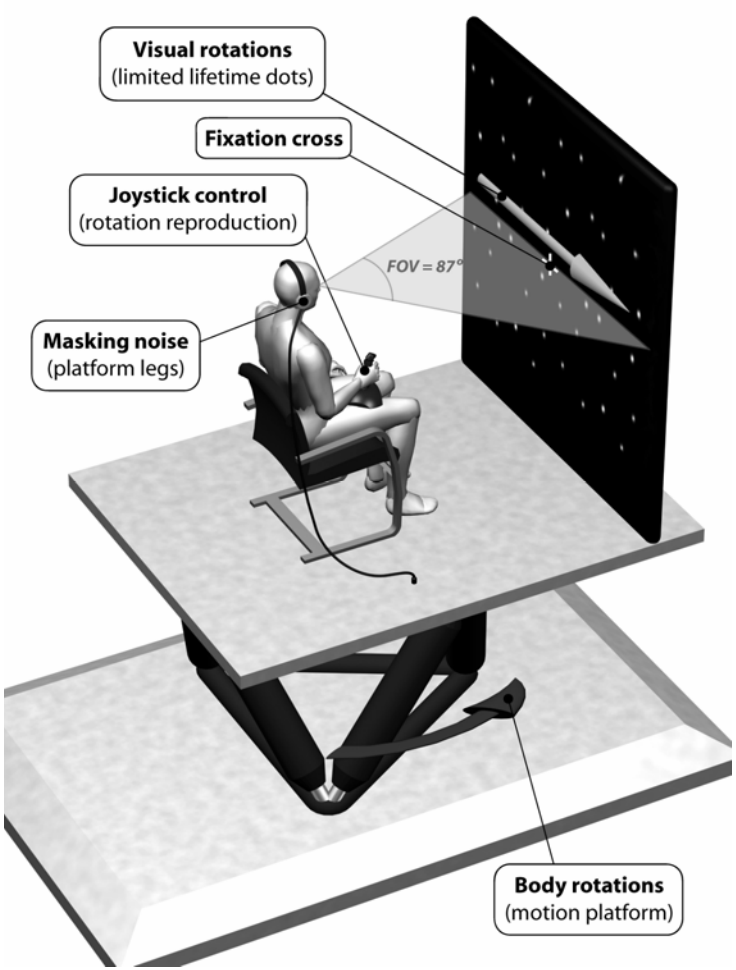
- Perception of self-motion is **multimodal**:
  - Visual modality
  - Vestibular modality
  - Other body senses

    Pilots: seat-of-the-pants feeling

- How are the different cues combined for the perception of self-motion?
- Does integration change if we **attend** to one cue or become **aware** of conflicts between cues?

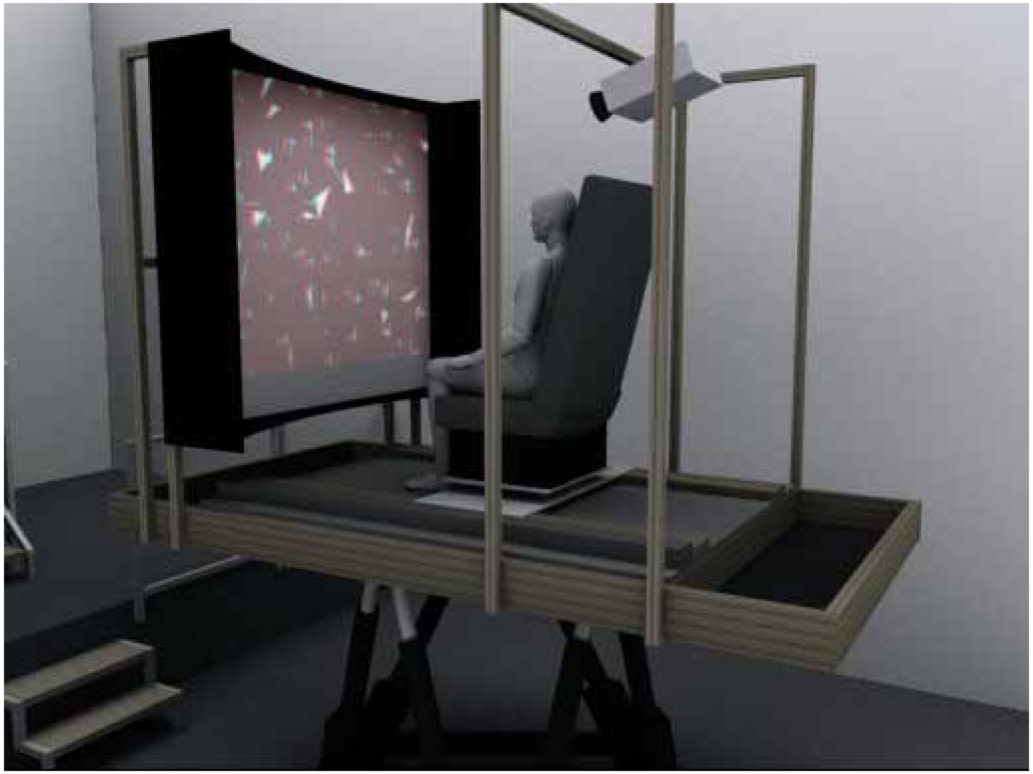
Daniel Berger, PhD thesis 2005

Multi-sensory Integration in the motion lab



Passive Rotation

scene and body



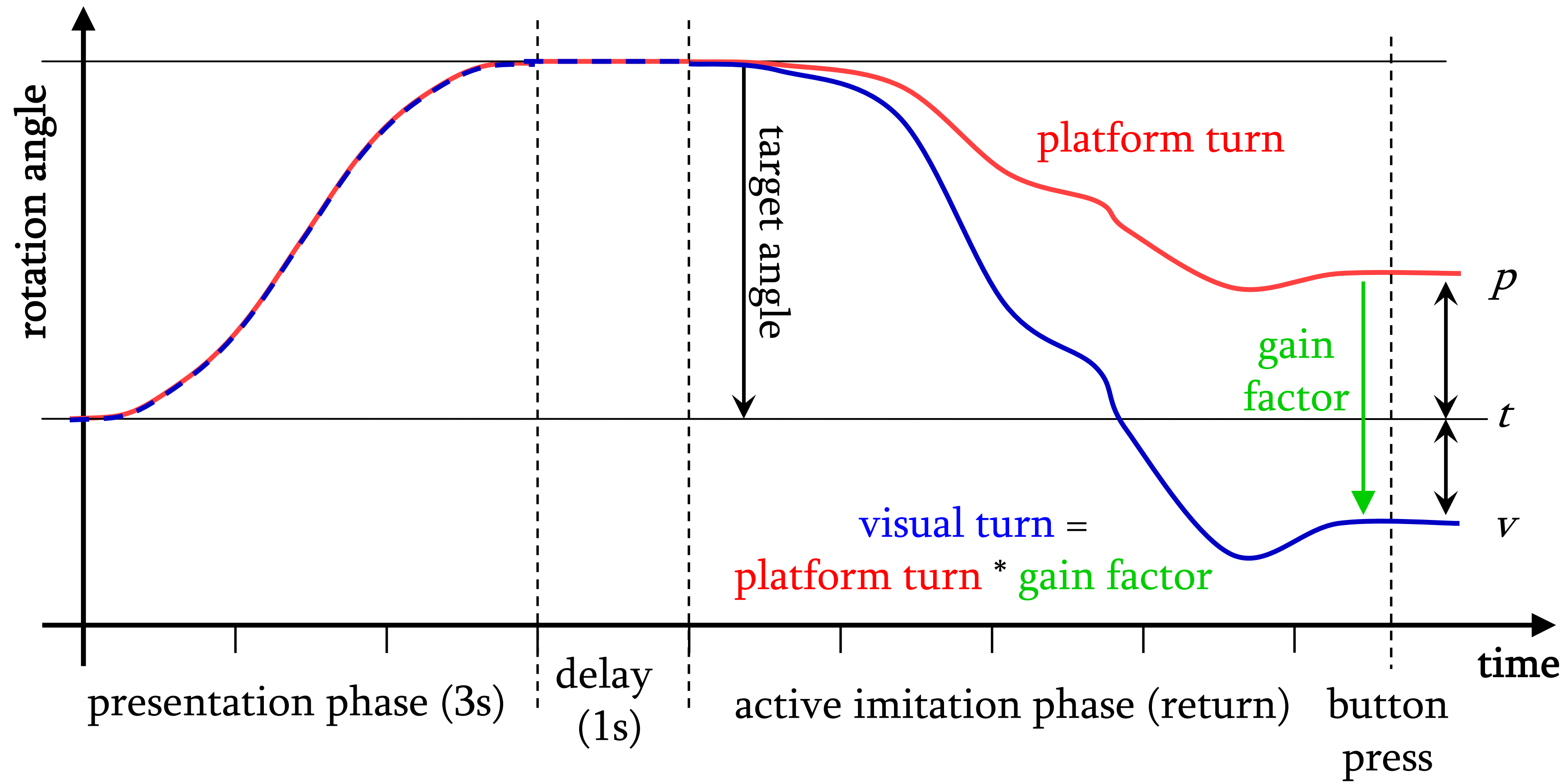
Active return to start position

gain between scene and body rotation

Cue conflicts between visual and body cues

- **Task**: Return an upright (yaw) rotation which has been presented with **both visual and body motion**
- **Trick**: During active return, a gain factor is introduced between the modalities
- **Report**: After each return, the participant has to indicate whether a **cue conflict was noticed** or not
  - Participants were told explicitly about possible cue conflicts

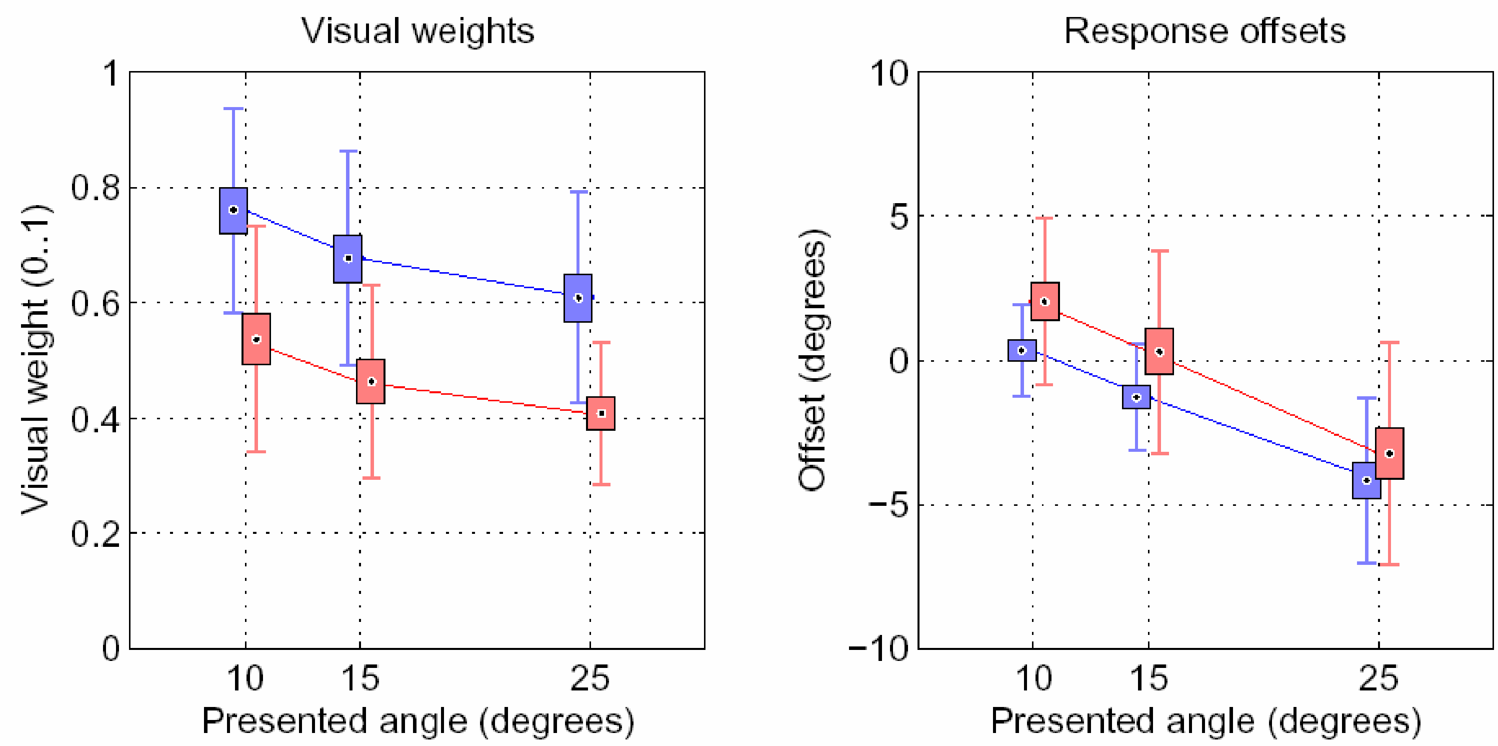
Movement compensation



Experimental Design

- **Method**: **Passively presented turn angles**: either 10°, 15° or 25°
- **Task**: return to start position (joystick control of motion)
  - **Gain factors** during active return: either 0.35, 0.71, 1.0, 1.41 or 2.85
- **Design: Two attention conditions**:
  - "turn back the platform" (**RBody**)
  - "turn back within the visual scene" (**RVis**)
- **Response**:
  - visual scene turned faster
  - platform turned faster
  - no difference noticed (**conflict awareness**)
- 20 participants (10 female, 10 male)
- 120 trials per block (3 angles, 5 factors, 8 repetitions)

Cue Weights and Attention



- Visual attention (RVis): "Return within visual scene"
- Body attention (RBody): "Return platform"

Conclusions

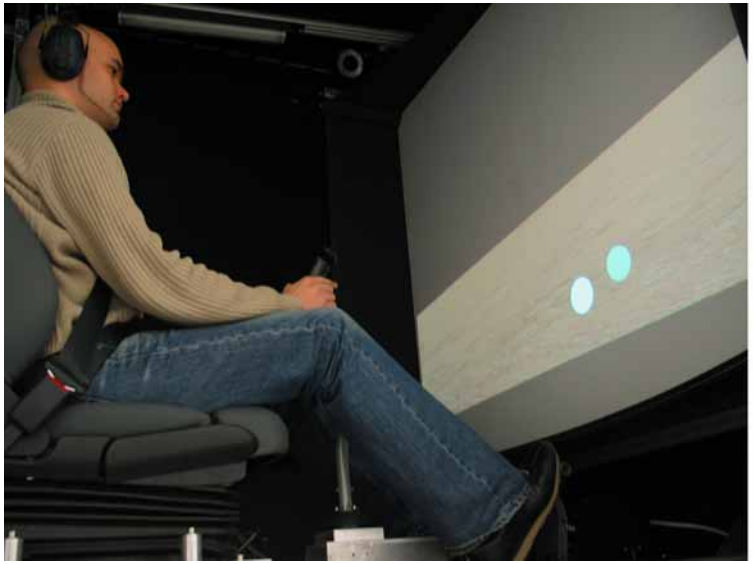
- Higher visual weights for small turns
- Attention modulates the weighting
- Attended cues have higher weights
- The influence of attention on cue weights is stronger in trials in which a cue conflict is detected by the participant

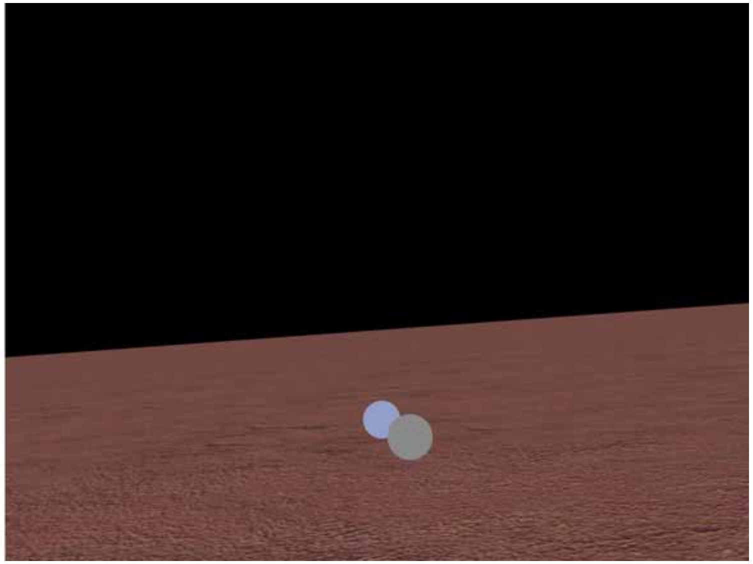
Multimodal Integration for Control tasks

- control task pose a whole new set of problems for integration
- new research direction of our lab
- how are cues integrated during active control of orientation in space
  - 3D maze navigation *(Manuel Vidal, 2004)*
  - body sway (*Cunningham et al, 2006*)
  - flight control *(Beykirch et al, 2006)*
  - helicopter stabilization *(Terzibas and Berger, 2005)*

Integration for Control Tasks
Helicopter stabilization

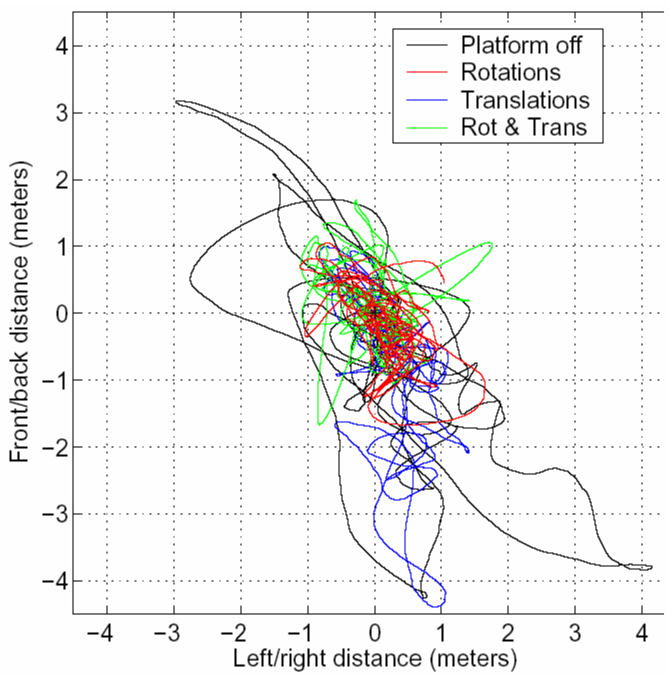
- Trained participants stabilize a simulated helicopter at a target spot
  - target ball on ground and ball representing the helicopter position
- Four different body motion cueing conditions:
  - **R:** platform (pitch and roll) rotations
  - **T:** translations (front-back and left-right)
  - **T & R:** both rotations & translations, platform off

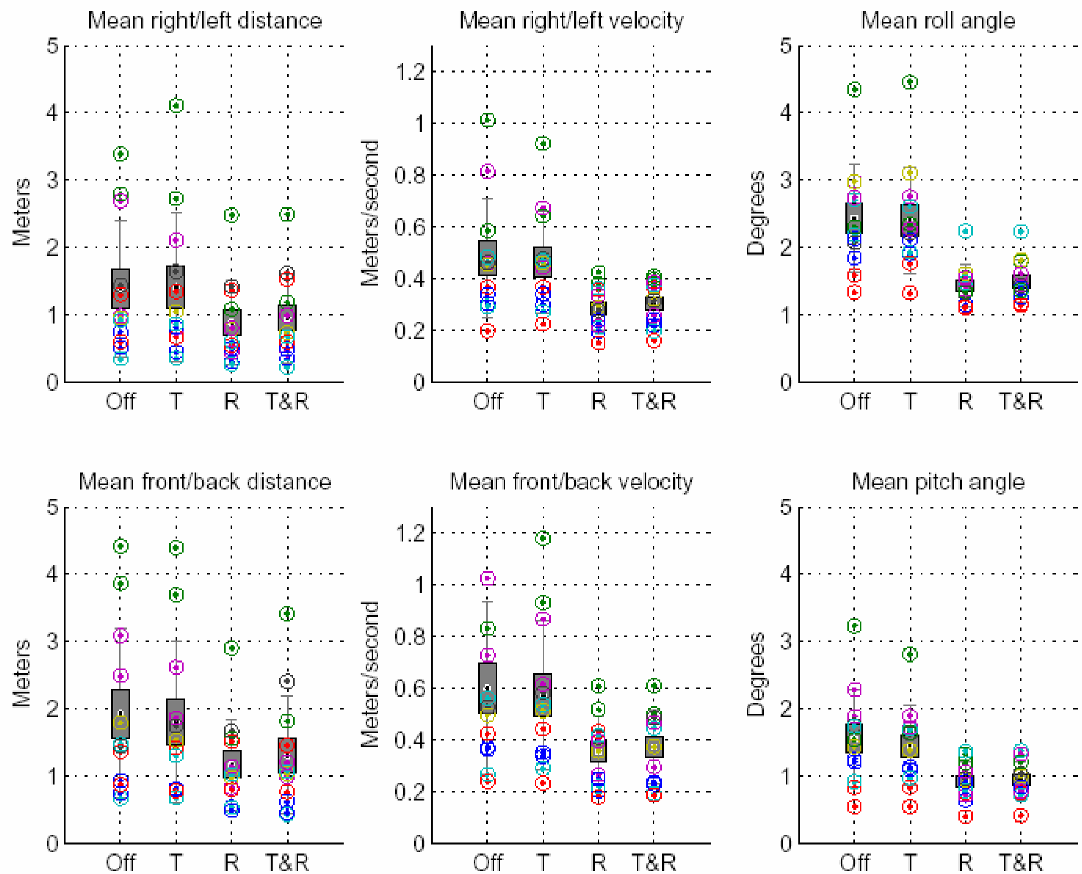




Results

Example Trajectories





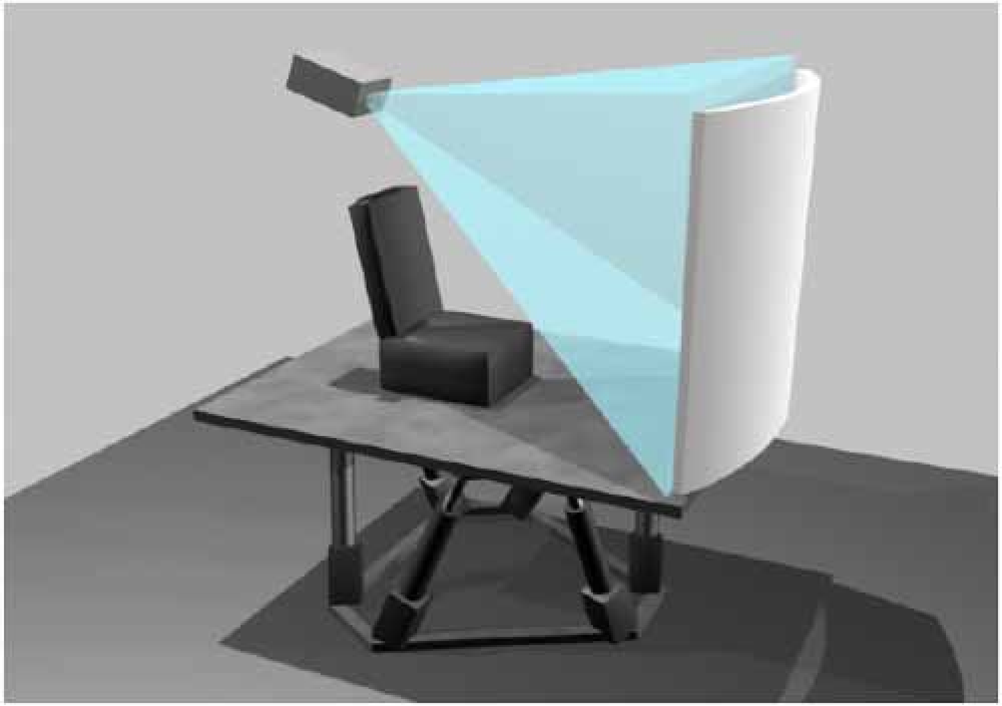
Off: platform off, T: translations, R: rotations

Results

- Stabilization performance significantly better in all six measures **with body rotations**
- **Body translations** had no significant effect on stabilization performance
  - Possibly translation simulation was not realistic enough (due to **range limitations** of the Stewart motion platform, wash-out filters had to be used)
- Better motion range with new motion simulator

Limitations of traditional motion simulators

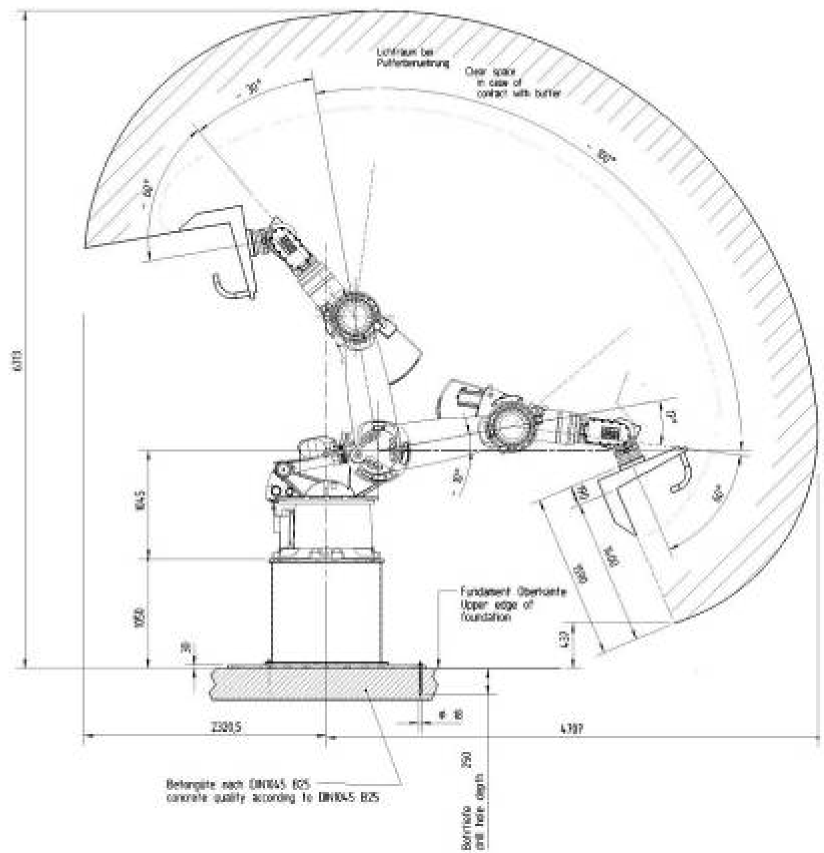
- 6-DOF but limited motion range
  - x: ± 0.46m
  - y: ± 0.43m
  - z: ± 0.25m
  - yaw: ± 44 deg
  - pitch: ± 33 deg
  - roll: ± 28 deg
- Recent attempts to overcome these limitations
- Kuka Robocoaster



Stewart Platform at MPI Tübingen

MotionbaseTM

The MPI Motion Simulator
based on the KUKA Robocoaster©



Ultimate Motion Simulator
KUKA Robocoaster©

New Perception-Action Lab CYBERNEUM

- ***RoboLab***
  - Visual-vestibular integration
  - Egomotion simulation
  - Flight and driving simulator
- **TrackingLab** (15x12m)
  - Free Space Locomotion
  - Motion Capture (Vicon)
  - Motion Tracking (Vicon)
- **Cyberwalk** (EU IST-FP 6)
  - Omnidirectional Treadmill

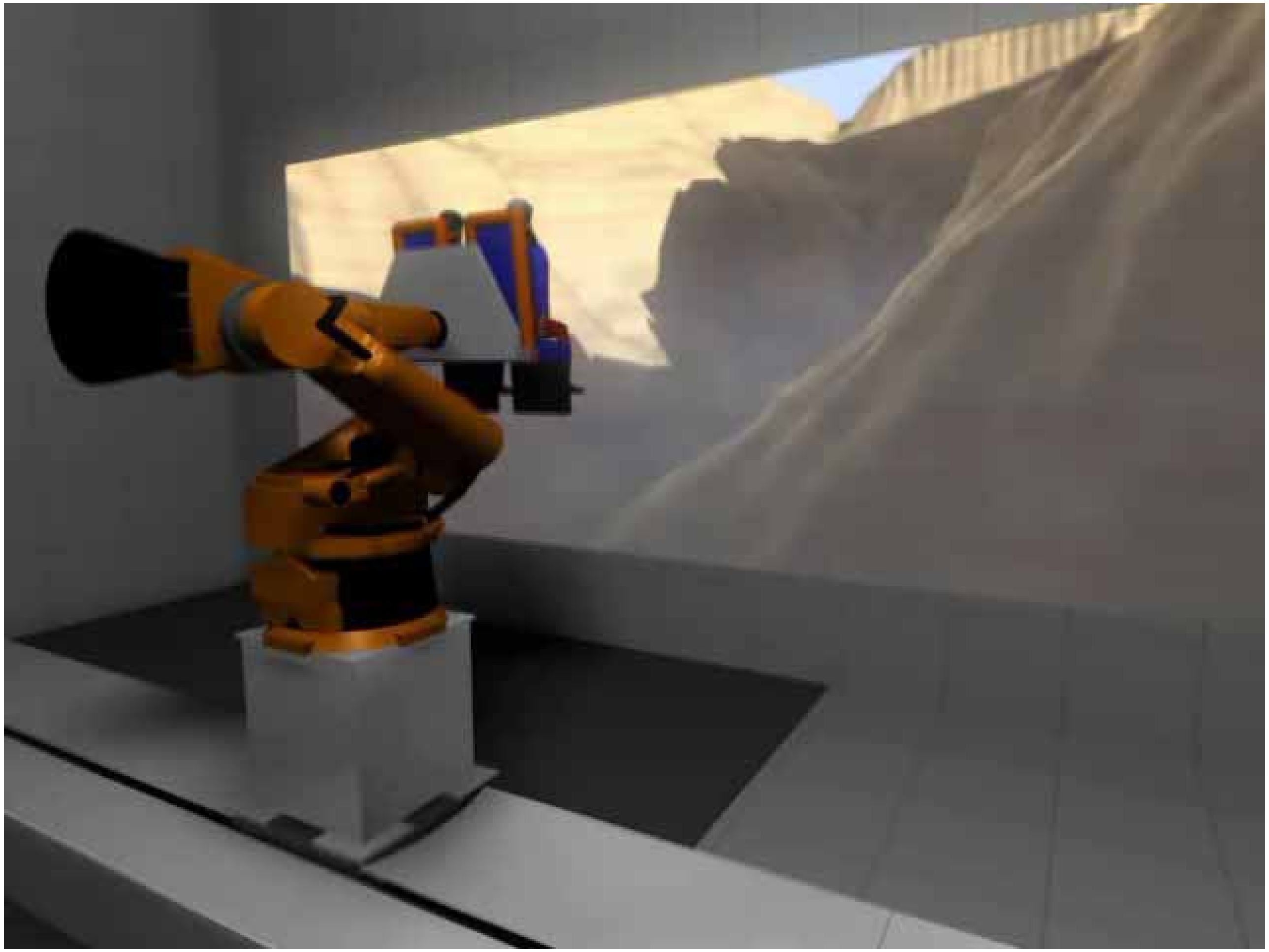
MPI Motion Simulator

- robot arm with low inertia
  - width 11,20 m
  - height 6,75 m
  - weight 3600 kg
- brushless AC drives
- max speed 2m/sec
- commercial platform with safety approval
- but needs visual display
  - HMD
  - dome projection
  - wall projection

Next Generation Flight Simulator

To extend the motion range even further we will put the RoboCoaster on a linear sledge

Ultimate Flight Simulator



Conservative estimate for motion range based on mechanical stops:
x: 1.6m (+ 8m)
y: 2.7m (+ 8m)
z: 1.2m
yaw: (unlimited)
pitch: ± 45 deg
roll: unlimited

x or y can be extended by **8m** with the linear sled

Future Plans in collaboration with DLR

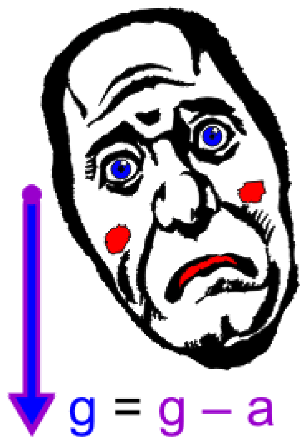
- Similar to the DLR Mars Mission using an Elumens™ projection system we plan to build a spherical projector on a modified single seat Robocoaster.
- Extend the motion range by replacing mechanical end stops with a failsafe end stop and closed-loop control system.

Towards a Better Understanding of Motion Simulation: A human perspective

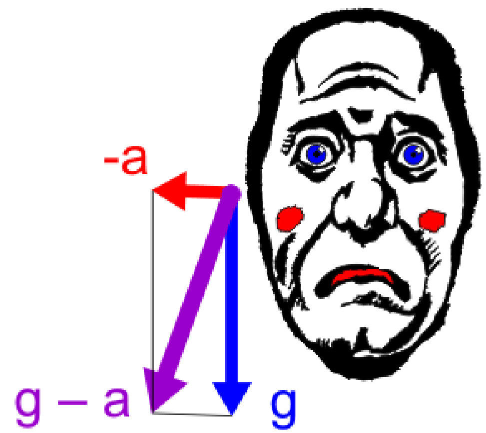
With this new setup, we hope to further elucidate the way the human brain processes the various cues to egomotion, **thus adding a human perspective to simulator design.**

1. Project
Tilt-Translation Ambiguity

- Einstein said, no sensor can distinguish gravity from translational acceleration.
- This holds also for our otolith organs – they sense gravity *minus* acceleration – so they can't distinguish certain tilts and motions.
- Yet the brain can usually resolve the ambiguity.
- How?



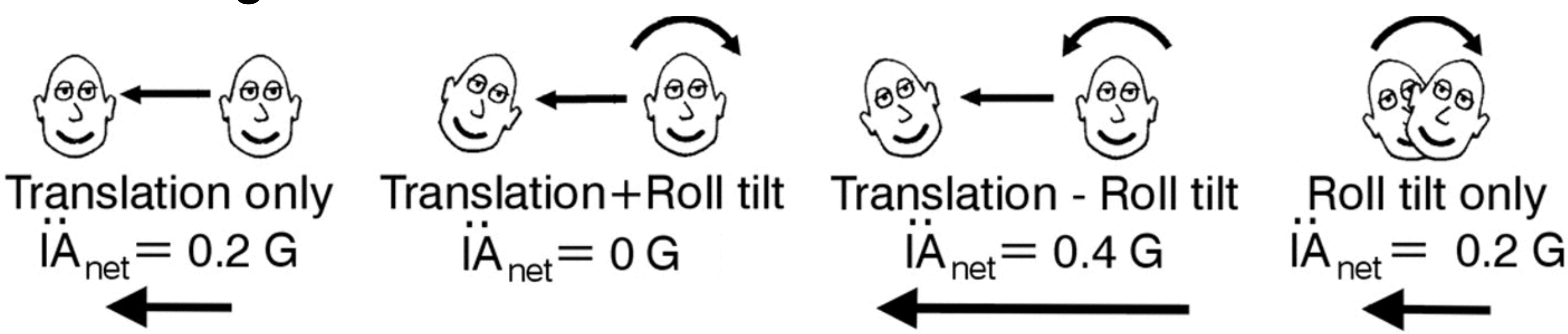
Tilt without translation



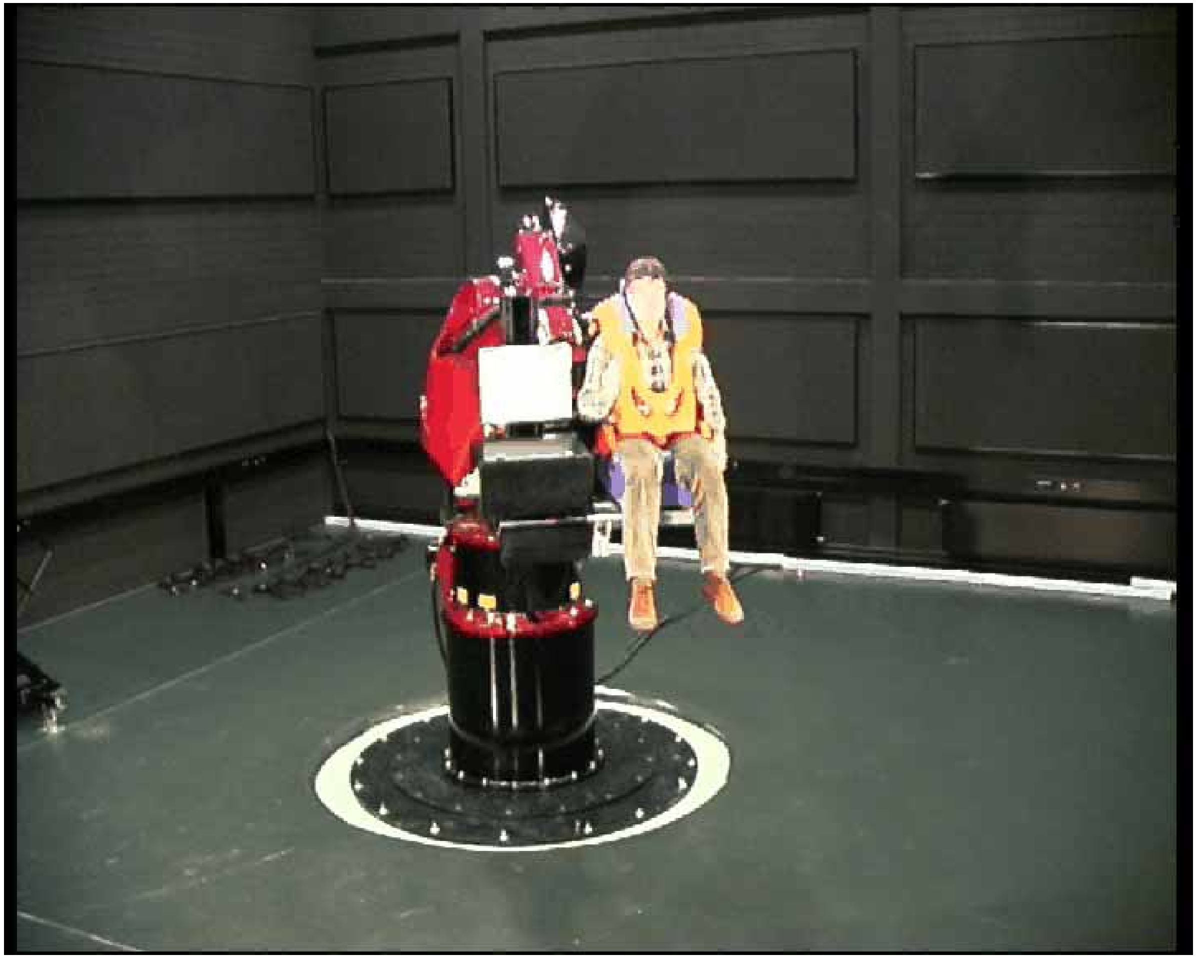
Translation without tilt

Tilt-Translation Disambiguation

- Temporal properties: tilt may be sustained, acceleration seldom is (Paige & Tomko 1991).
- Multisensory integration: semicircular canals detect rotation (Angelaki & Hess 2000, Zupan et al. 2002).
- We'll test these theories in humans and more precisely than in previous studies, e.g., we'll control the magnitude of the gravitoinertial vector.

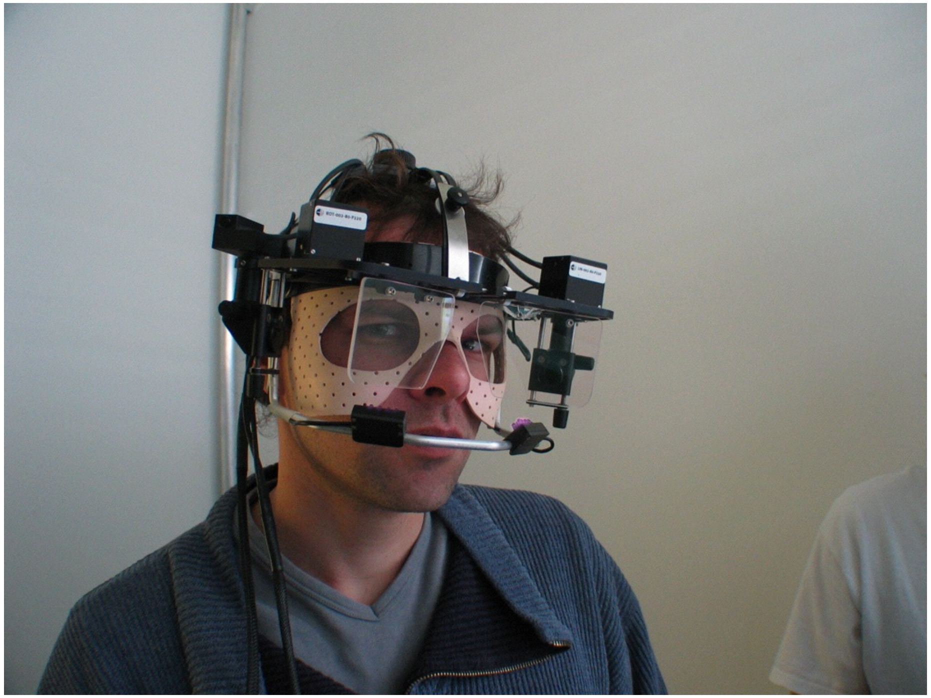


Tilt-Translation Experiment



Response Measure

Use eye-moment as a physiological response measure for acceleration response of otoliths.
x,y + cyclotorsion of eye movement movements



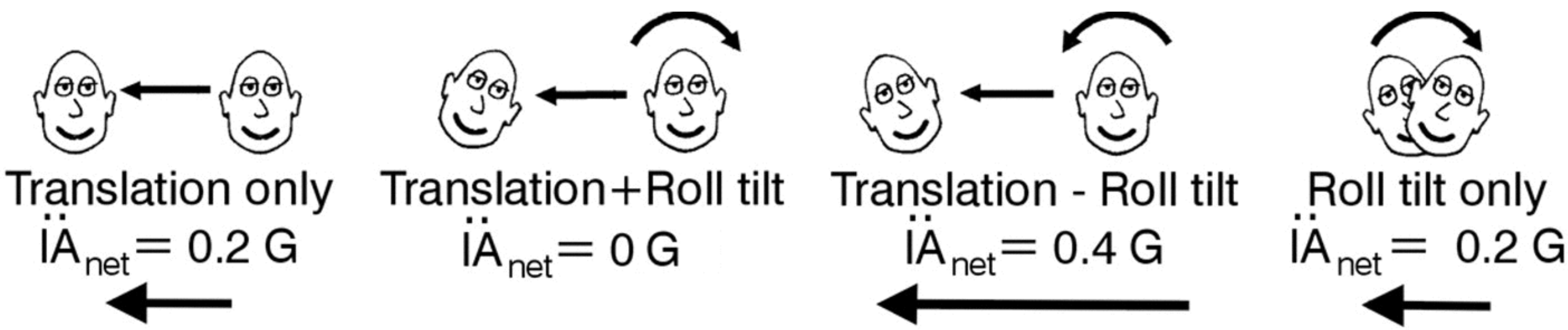
- CMOS image sensors
- 400 Hz
- Face mask
- Bite bar
- torsional eye recording
- Resolution: < 0.1°
- Linearity: < 2.5% +/- 20° H/V
  <4.0% +/- 20° T
- Accelerometers: 1mg

Chronos 3D Eye Tracker

Tilt-Translation Disambiguation

Further questions:

- Can disambiguation adapt?
- Do oculo-motor adaptations affect perception?
- Can adaptation training modify spatial disorientation in pilots?

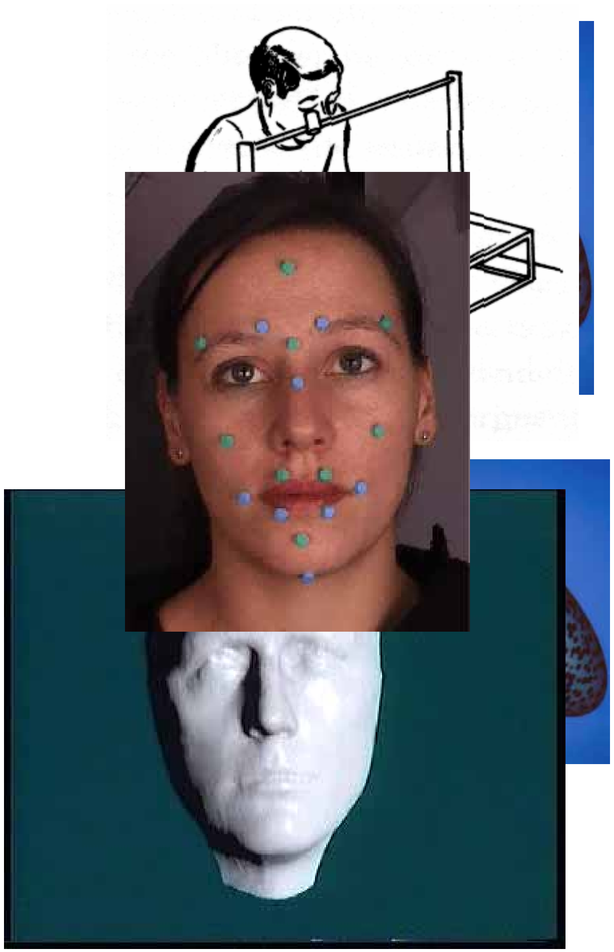


Long Term Goals

- Pursue a practical understanding of the neural processing of multi-sensory self-movement information.
- Explore relationship between physiologic (eye movements) and perceptual data of self-motion in humans.
- Evaluate existing models of this type of response.

Review

- Sensor fusion takes place at all levels
  - early vision
    - stereo, shading, texture, motion, …
  - between modules
    - vision, vestibular, auditory, …
  - higher cognitive levels
    - recognition, emotion
- Sensor fusion use all modes of interaction
  - accumulation or joint regularization
    - shape-from-x
  - cooperation or strong fusion
    - shading and texture
  - disambiguation
    - stereo disambiguates shading (rotating mask)



Conclusion

- sensor fusion works in many cases in a statistical optimal way
- the brain seems to know Bayesian statistics
- but there are also many other ways how the brain can make sense of the world

Members of the new perception-action lab


Daniel Berger


Karl Beykirch


Astros Chatziastros

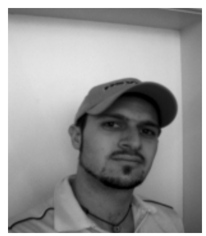

Reinhard Feiler


Gerald Franz


Paolo Pretto


Franck Caniard


Hans-Günther Nusseck


Andreas Wacker


Bernhard Riecke


Cengiz Terzibas


Jörg Schulte-Pelkum


Michael Weyel


Marc Ernst

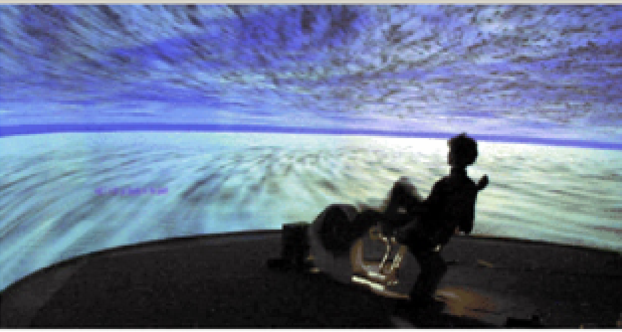

Harald Teufel


Heinrich Bülthoff


Jan Wiener


Manuel Vidal

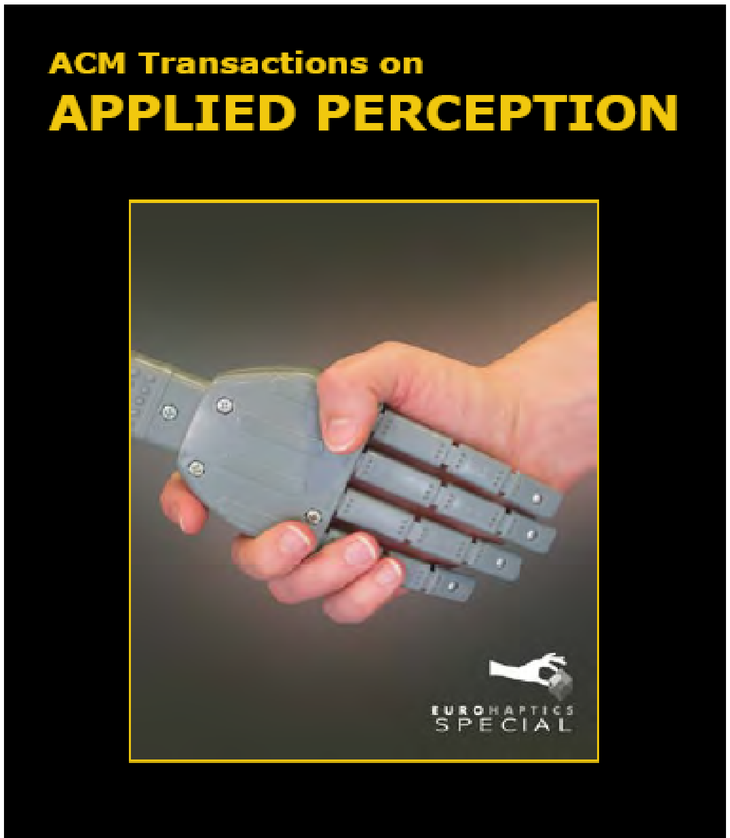
perception of ego-motion



research topics:

- visual cues for steering
- interaction between gaze, attention, and driving direction
- spatial updating
- visual-vestibular sensor fusion
- reference frames and field of view
- cognitive influence on reflexive behavior
- perceptually oriented ego-motion simulation (POEMS)

ACM Transactions on Applied Perception



An interdisciplinary journal to foster synergy between computer science and perception

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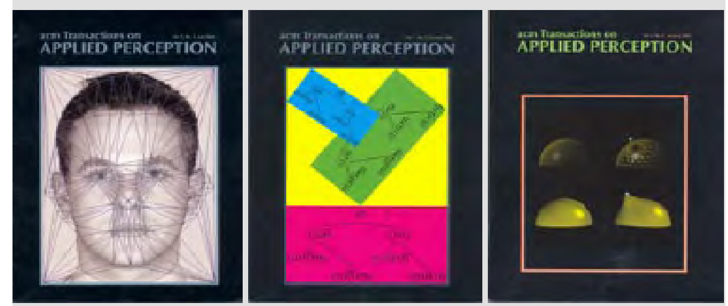

www.acm.org/tap

APGV

Applied Perception in Graphics and Visualization
Boston, before SIGGRAPH

- Interdisciplinary meeting to foster synergy
  - between perception and computer science
  - every year
- alternating between SIGGRAPH and ECVP
  This symposium seeks to provide a forum
  for the wider exchange of ideas and information
  - between members of the graphics and visualization communities who are using insights from visual/auditory/haptic perception to advance the design and guide the evaluation of methods for more effective visual/auditory/haptic representation,
  - and members of the vision sciences community who are using computer graphics to facilitate the investigation of fundamental processes of perception.