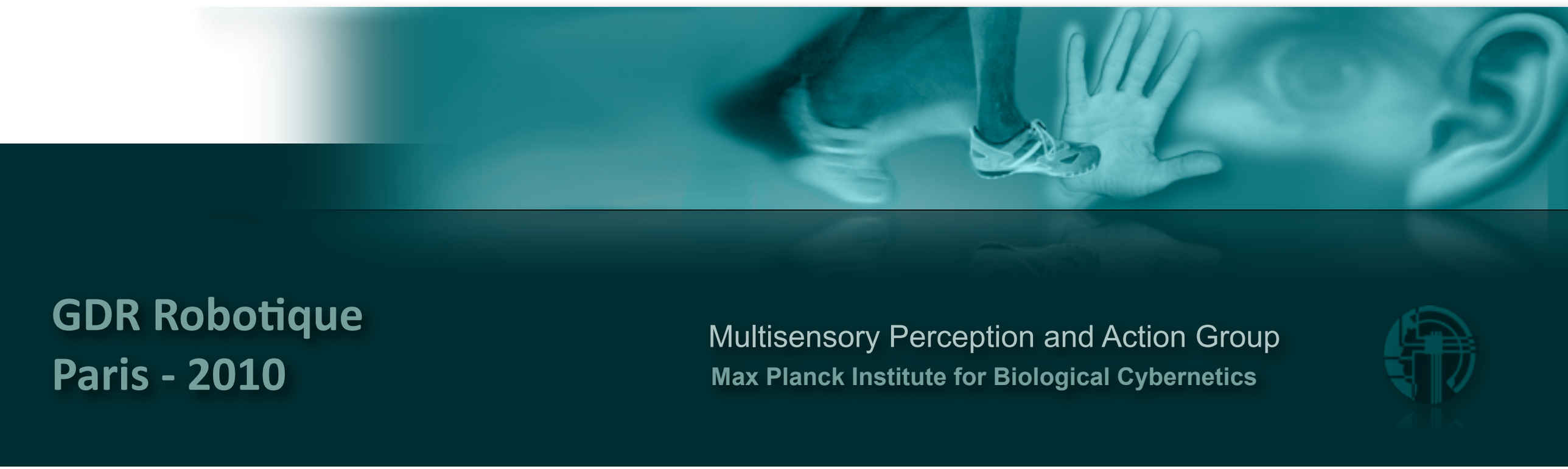
Human Multisensory Perception: putting the puzzle together

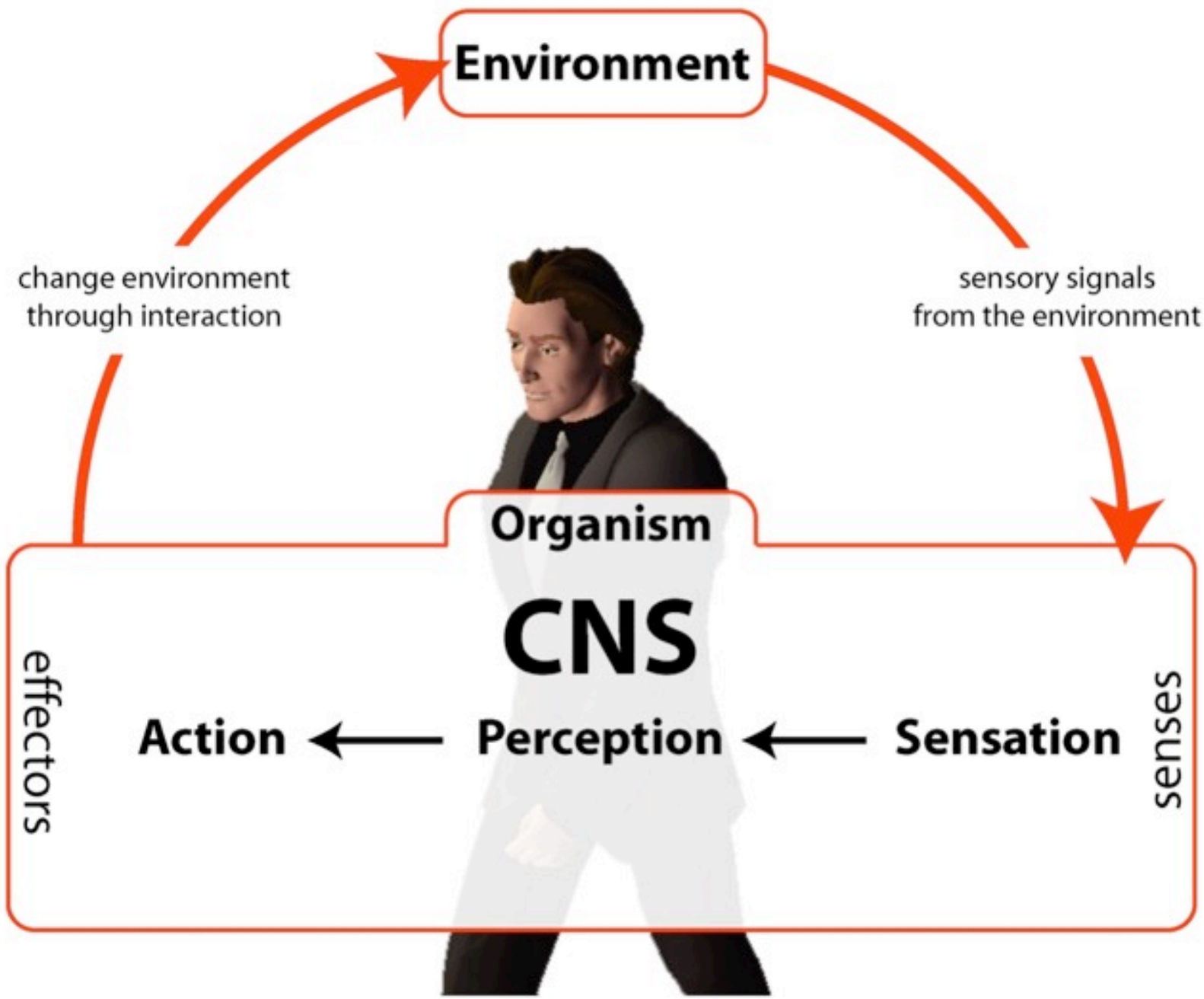
Marc O. Ernst



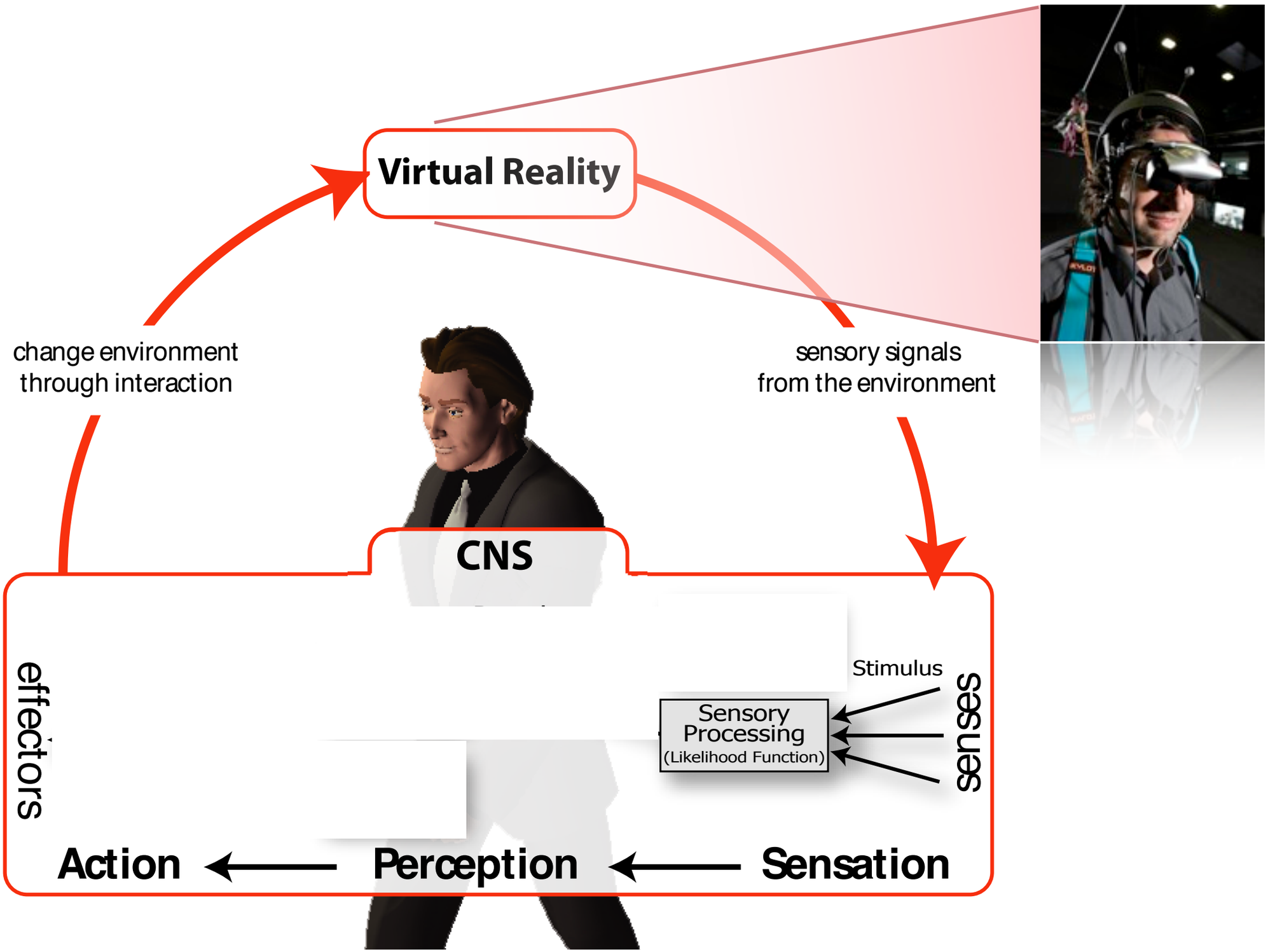
GDR Robotique
Paris - 2010

Multisensory Perception and Action Group
Max Planck Institute for Biological Cybernetics

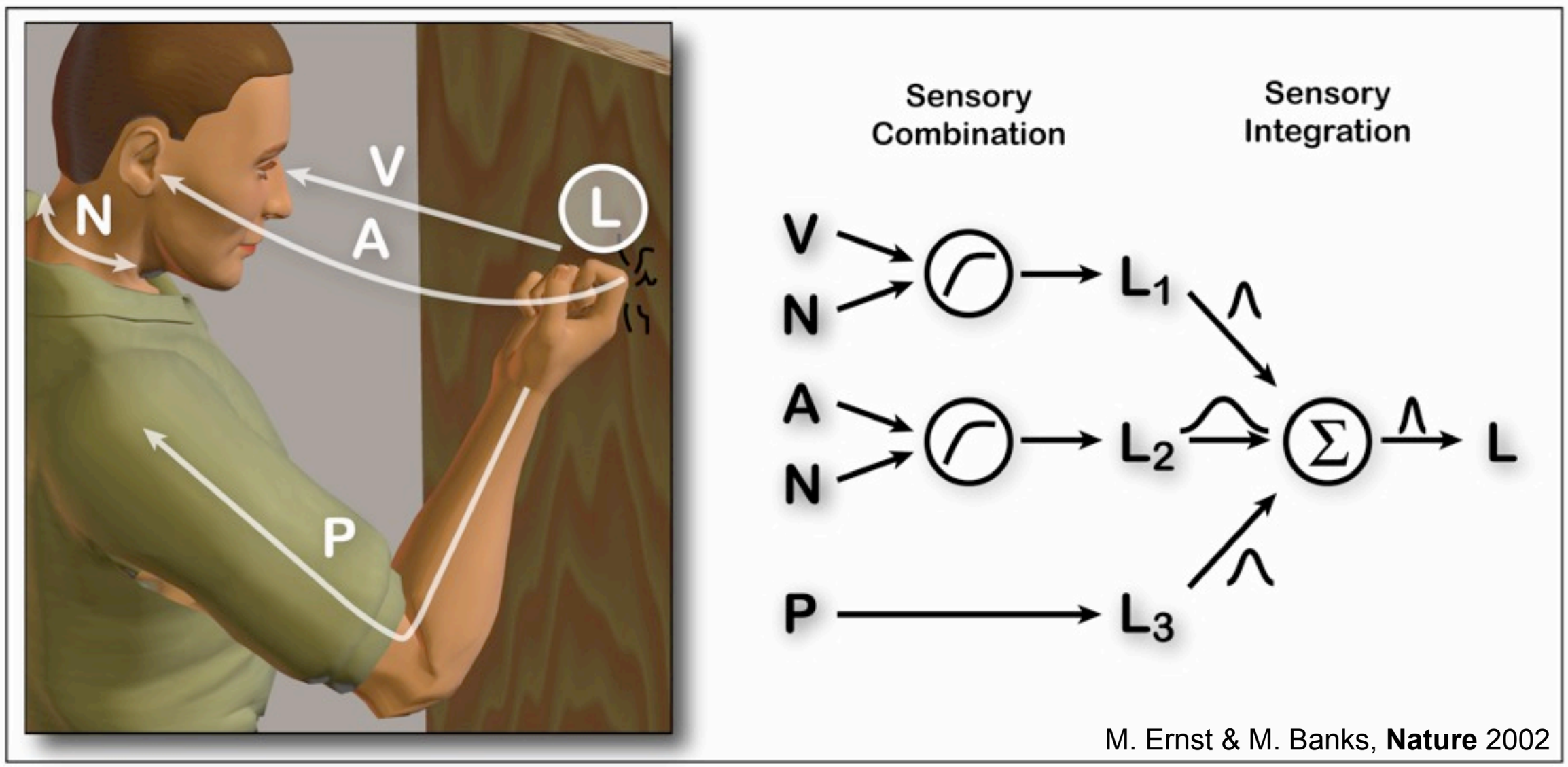
The world in our head to interact!



Perception for Action



Multisensory Integration

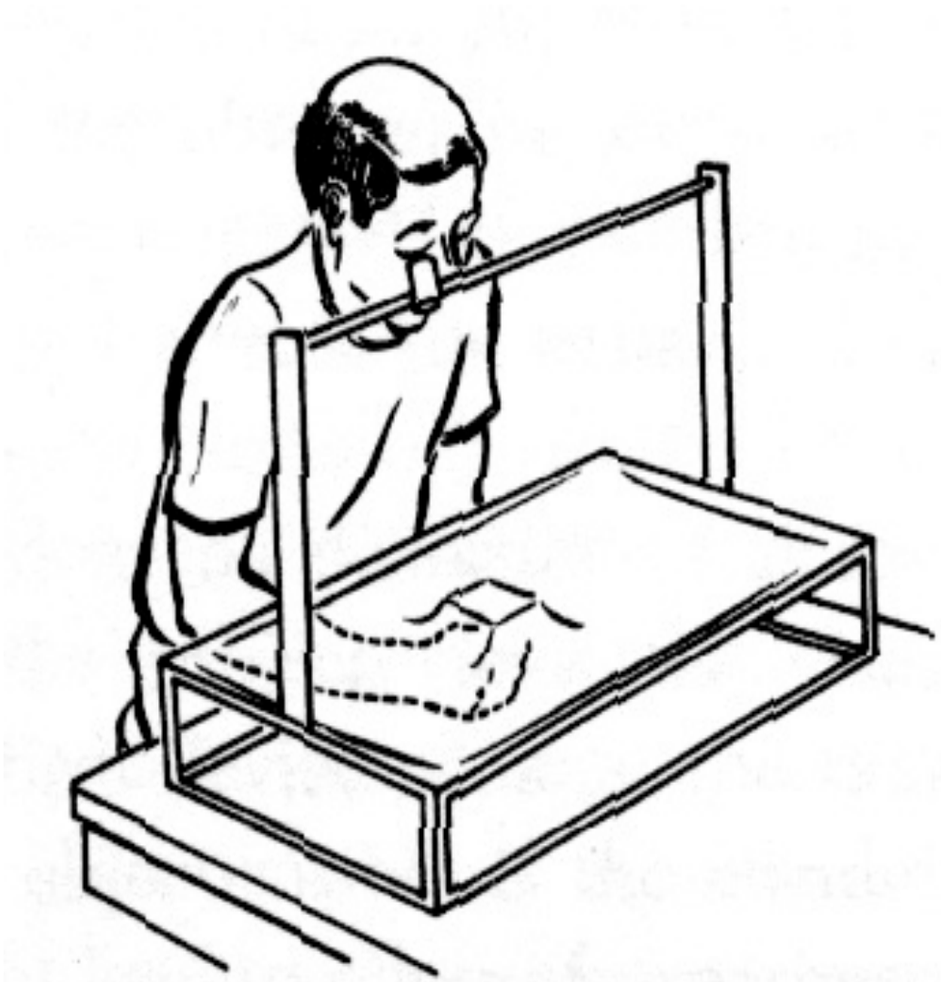


M. Ernst & M. Banks, **Nature** 2002

Rock & Victor (Science, 1964)

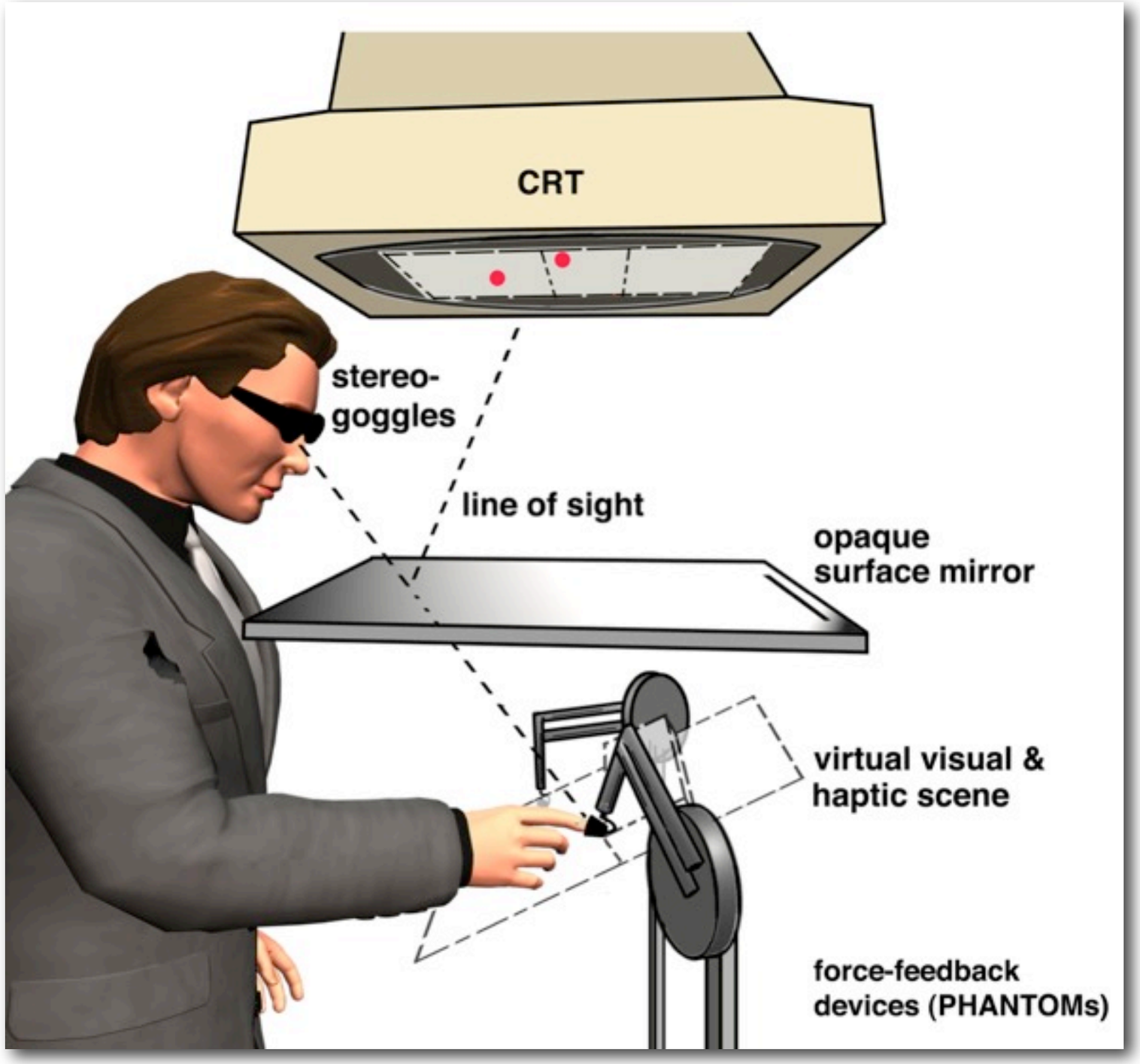
Irv Rock

Looking at an object through a distortion lens while touching the object.

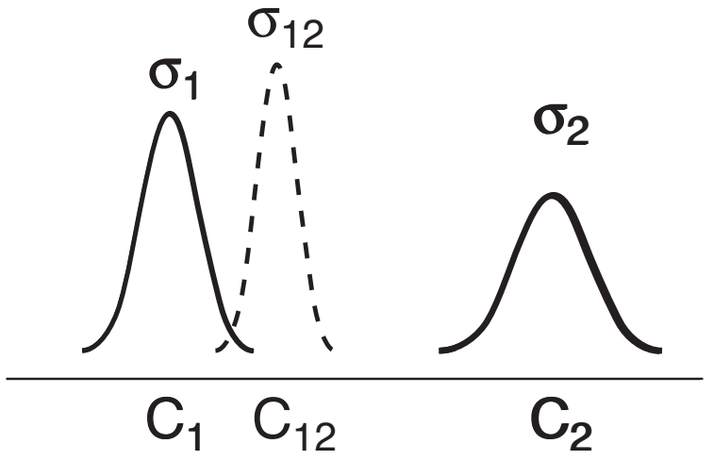


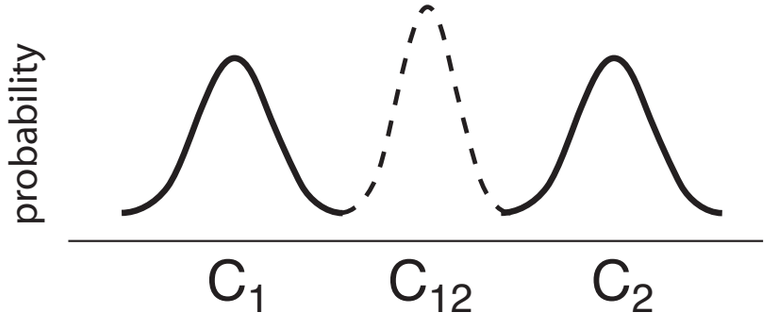
Discrepancy between visual and haptic form.
Which form is perceived? ➤ **Visual Capture**

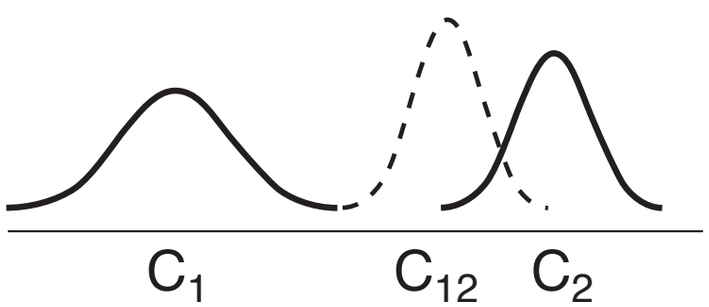
Visual-haptic Setup



Multisensory Integration

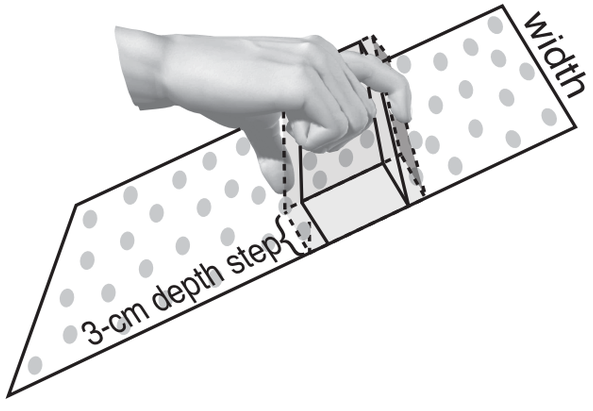






„ideal observer“ approach

visual-haptic cues to size



reliability

$$r_i = \frac{1}{\sigma_i^2}$$

weights

$$w_i = \frac{r_i}{\sum r_j}$$

weighted sum

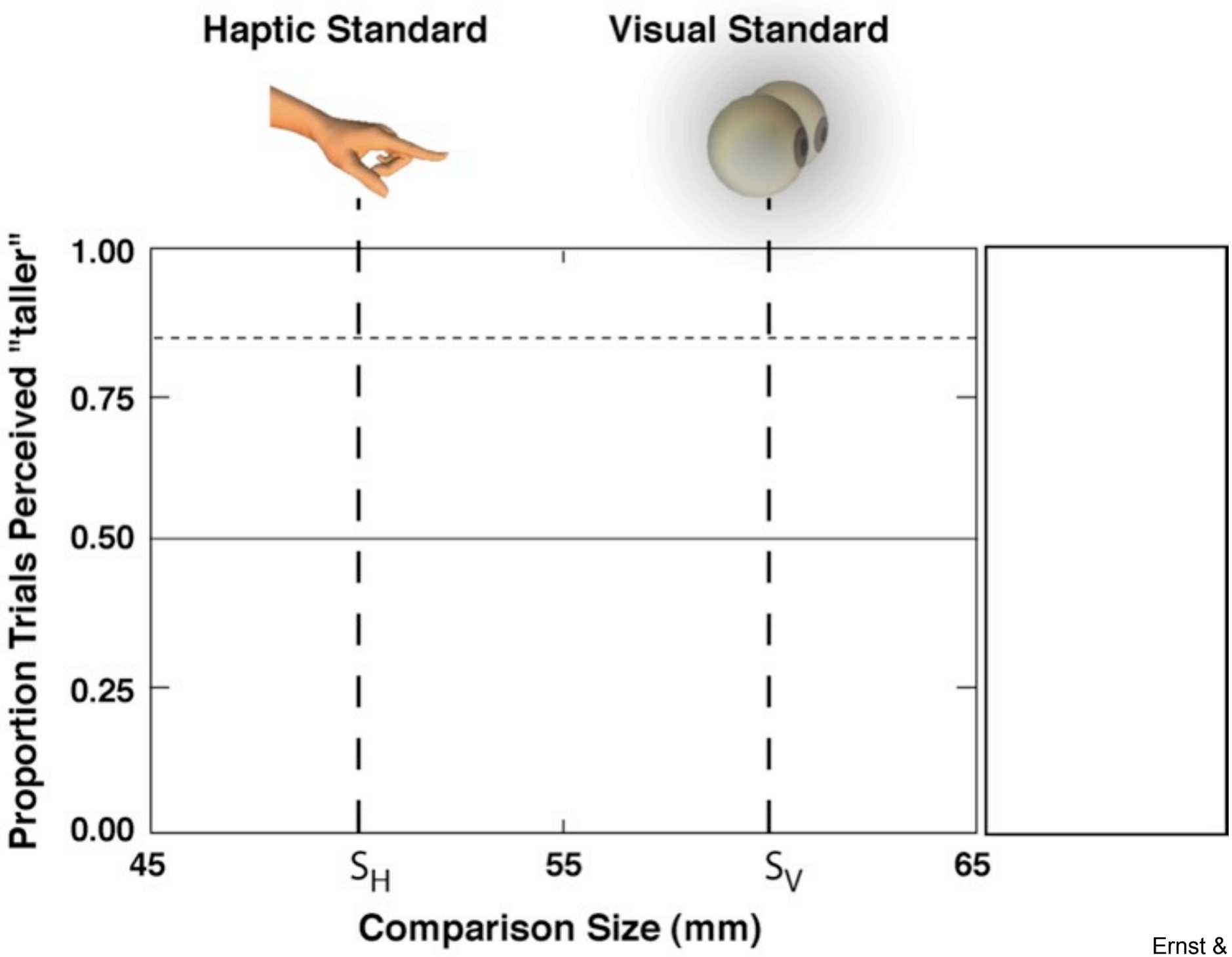
$$C_{12} = w_1 C_1 + w_2 C_2$$

combined reliability

$$r_{12} = r_1 + r_2$$

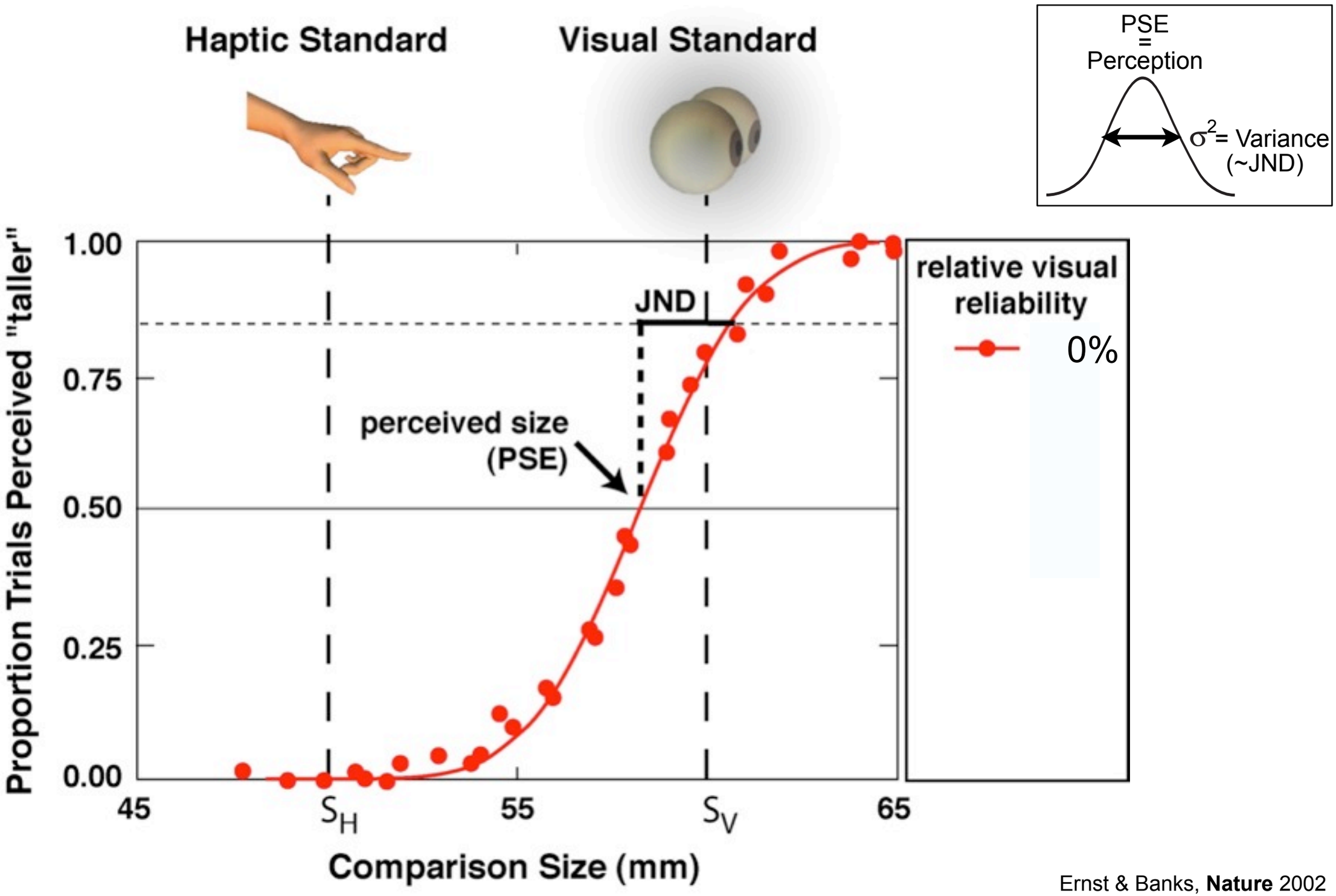
Ernst & Banks, **Nature** 2002

Visual-Haptic Integration



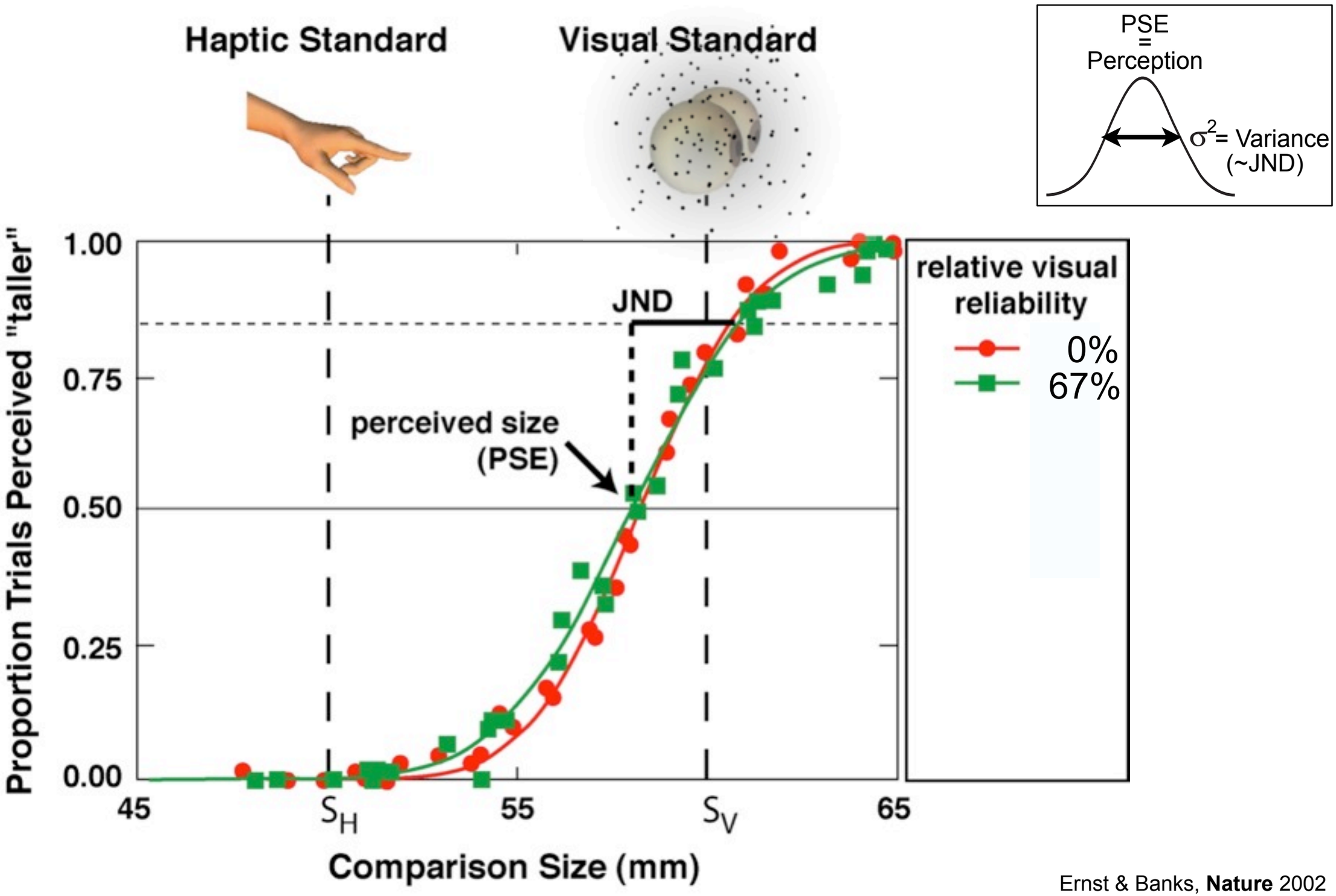
Ernst & Banks, **Nature** 2002

Visual-Haptic Integration



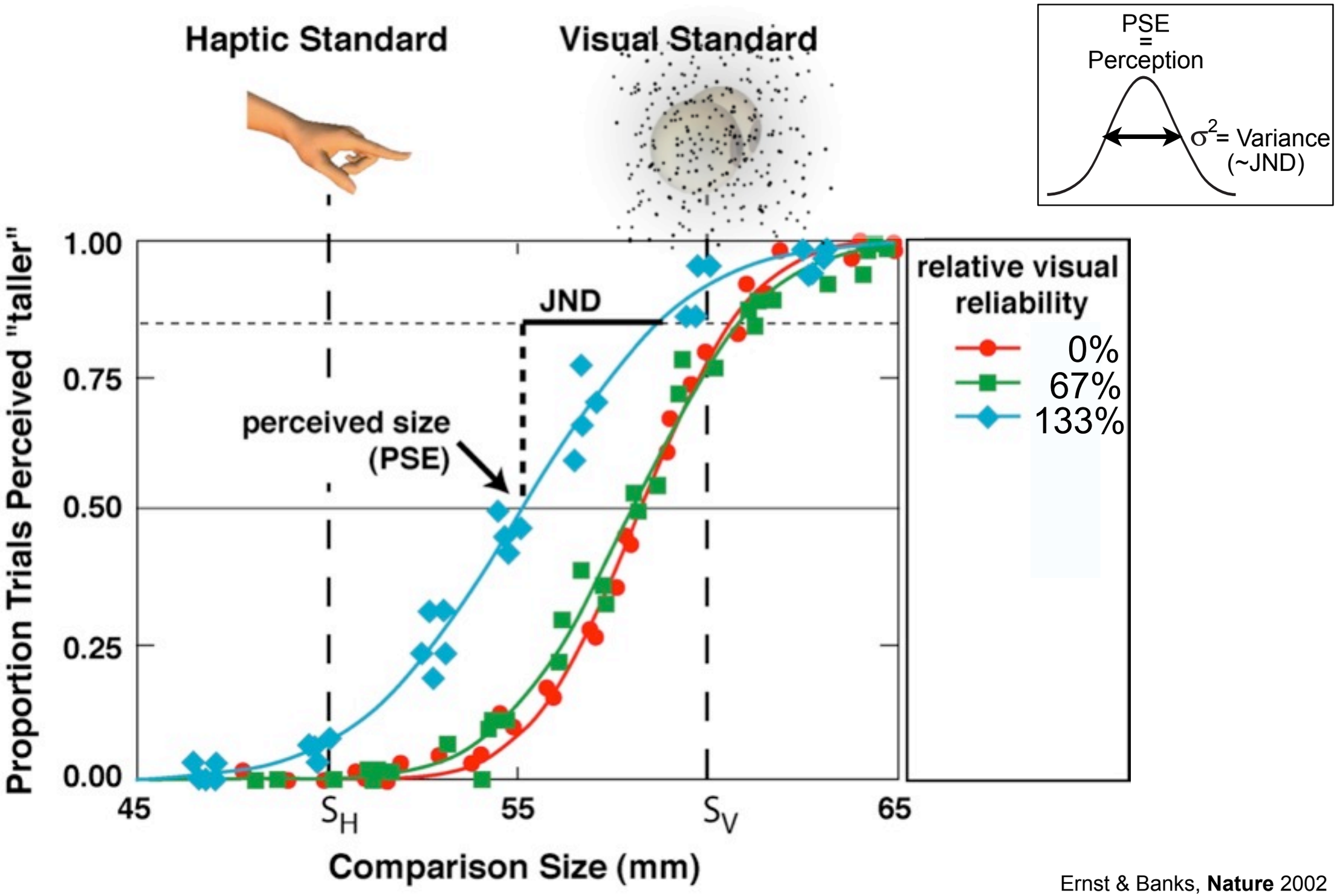
Ernst & Banks, **Nature** 2002

Visual-Haptic Integration



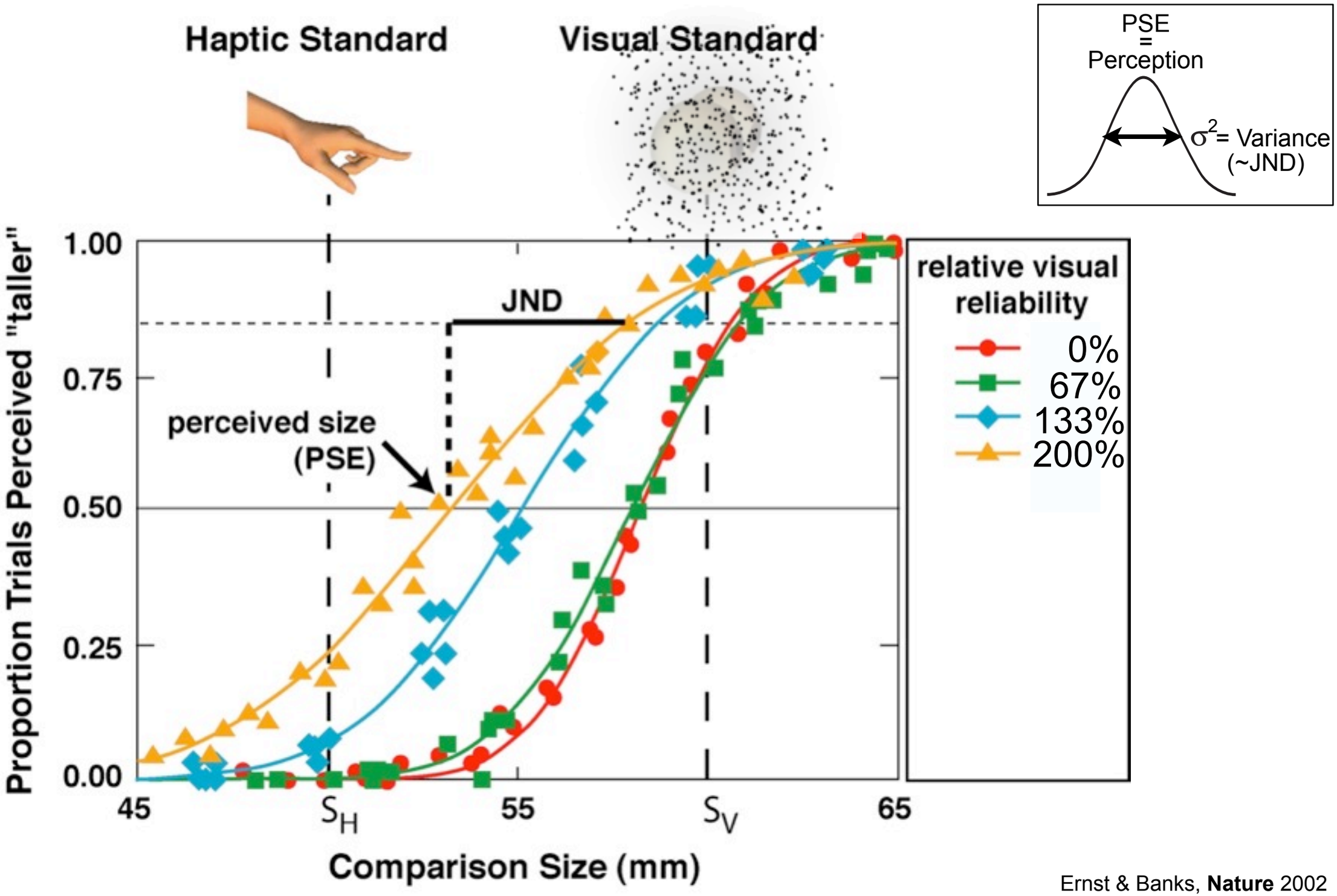
Ernst & Banks, **Nature** 2002

Visual-Haptic Integration



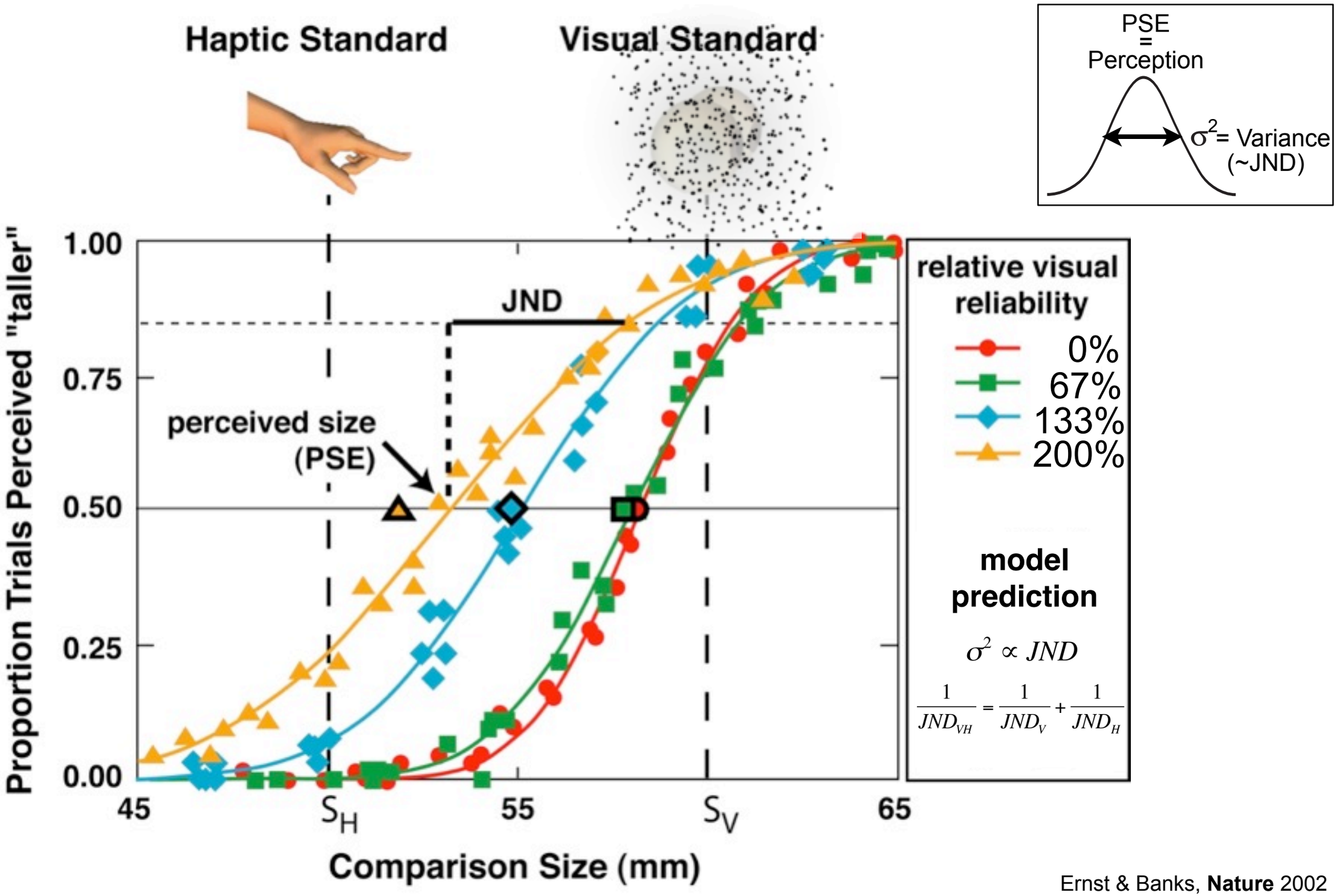
Ernst & Banks, **Nature** 2002

Visual-Haptic Integration



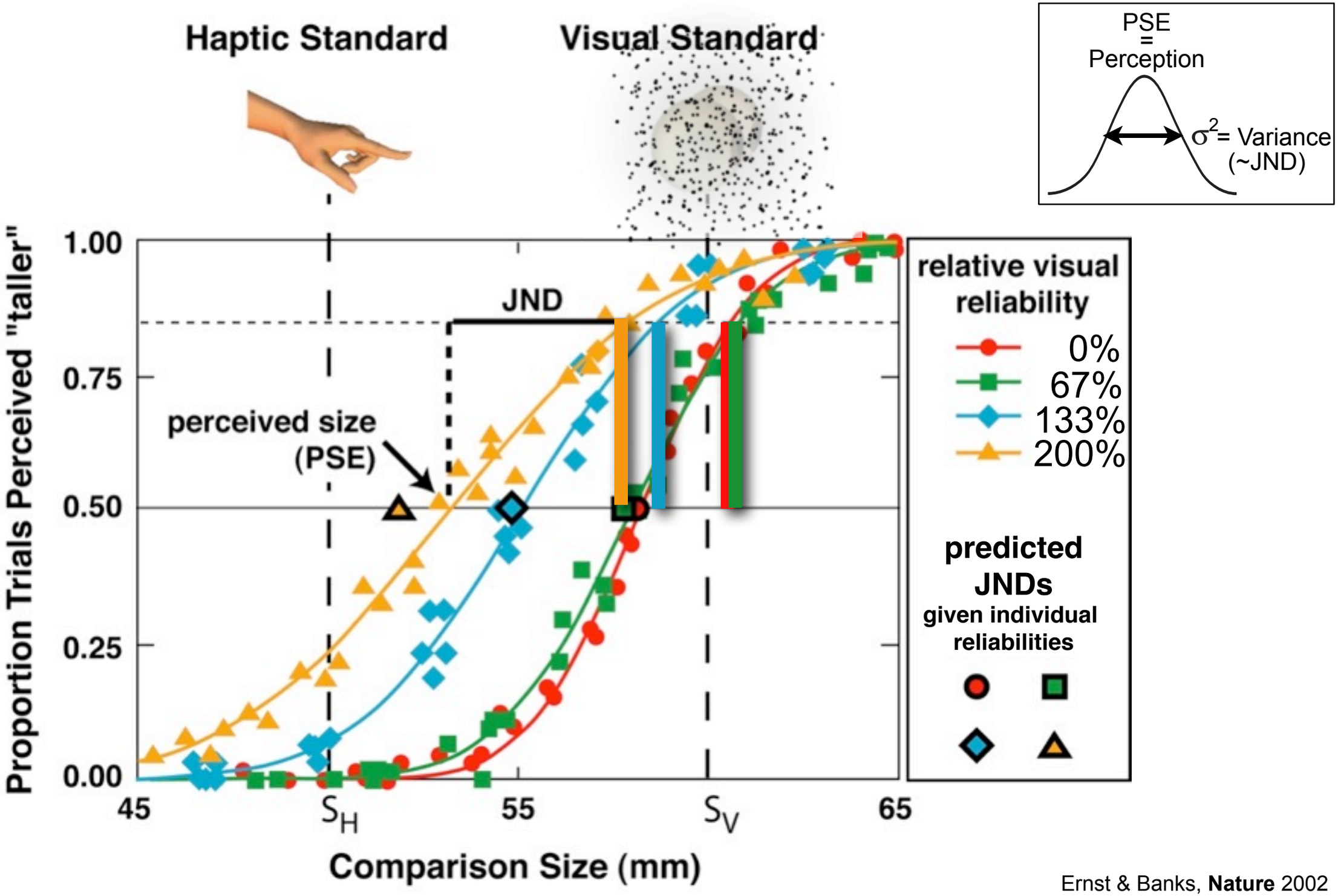
Ernst & Banks, **Nature** 2002

Visual-Haptic Integration



Ernst & Banks, **Nature** 2002

Visual-Haptic Integration



Ernst & Banks, **Nature** 2002

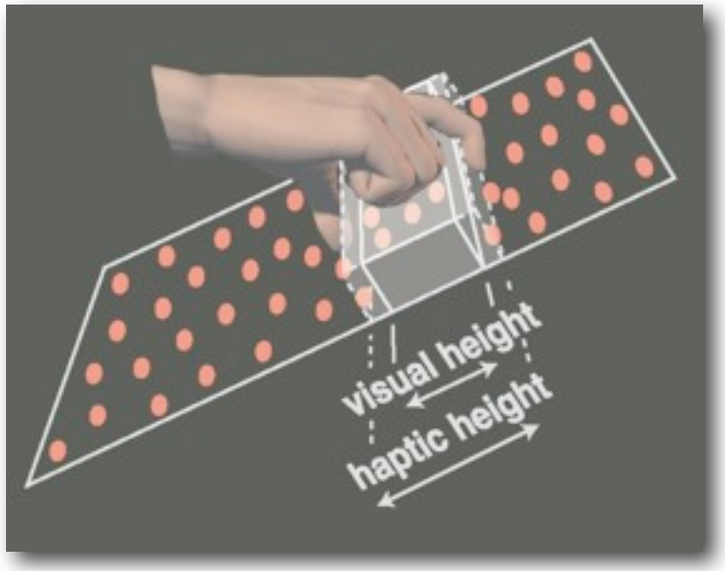
Visual-Haptic Integration: Conclusion

Humans integrate visual and haptic information in a statistically optimal fashion

Marc O. Ernst* & Martin S. Banks (2002)

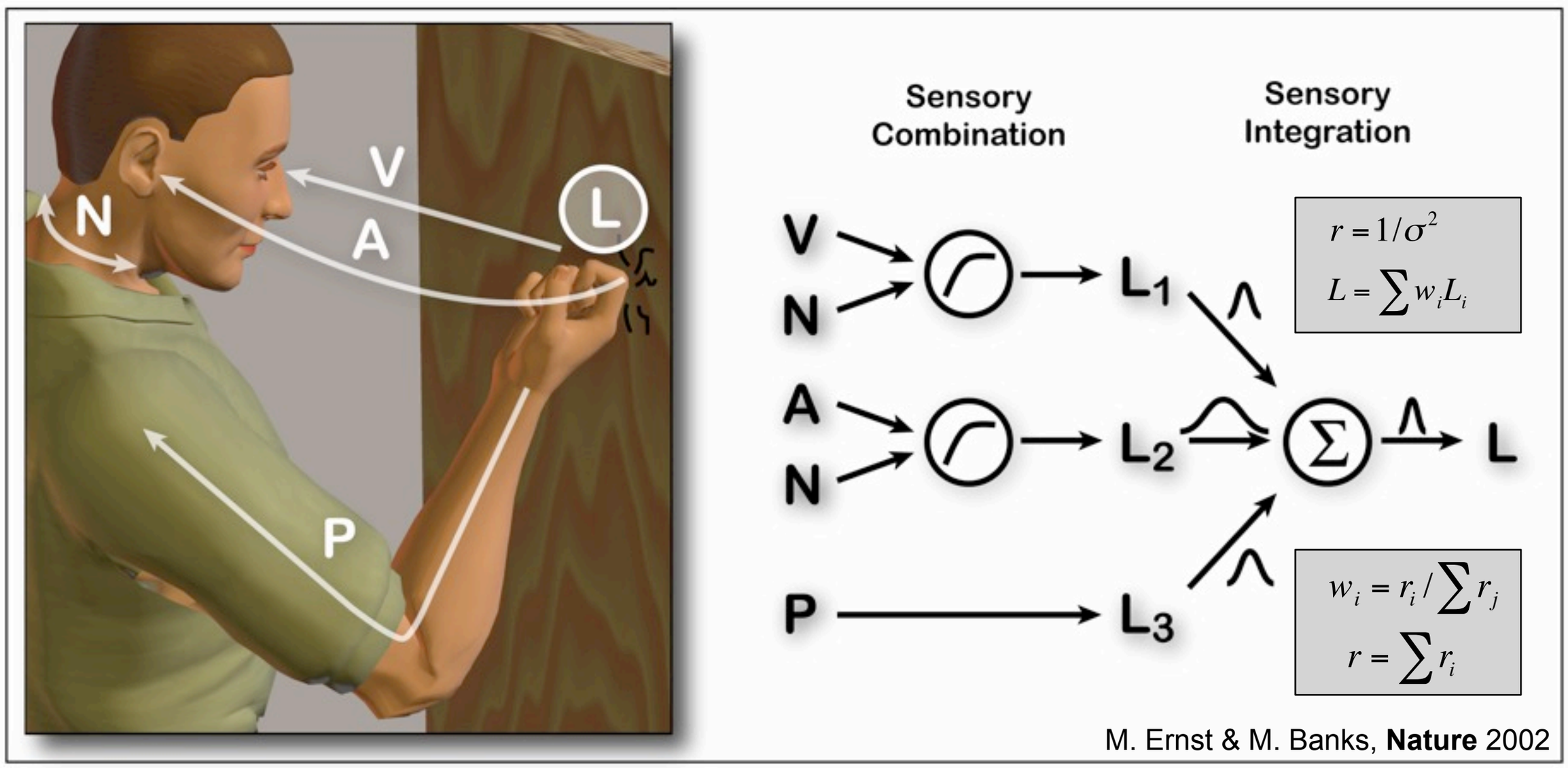
Vision Science Program/School of Optometry, University of California, Berkeley 94720-2020, USA

Nature 415, 429-433 (2002)



- **Signals are weighted according to their reliabilities**
- **Integration reduces variance (increases reliability)**
- **Online representation of signal and its reliability**

Multisensory Integration



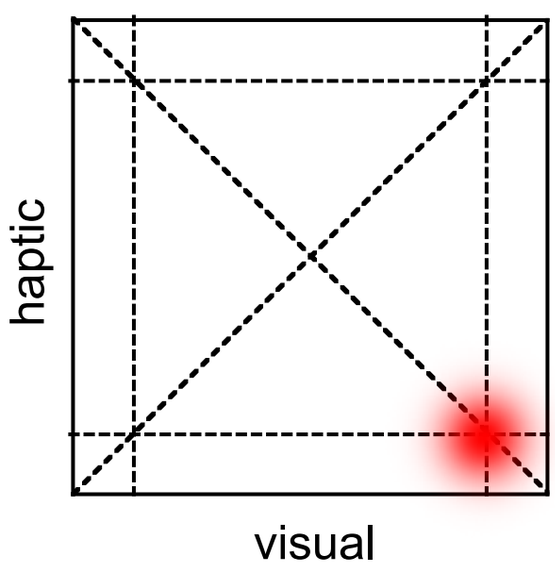
M. Ernst & M. Banks, **Nature** 2002

Assumptions:
- **signal correspondence (redundancy)**
- **unbiased**

➤ **Learning!!!**

Modelling Integration

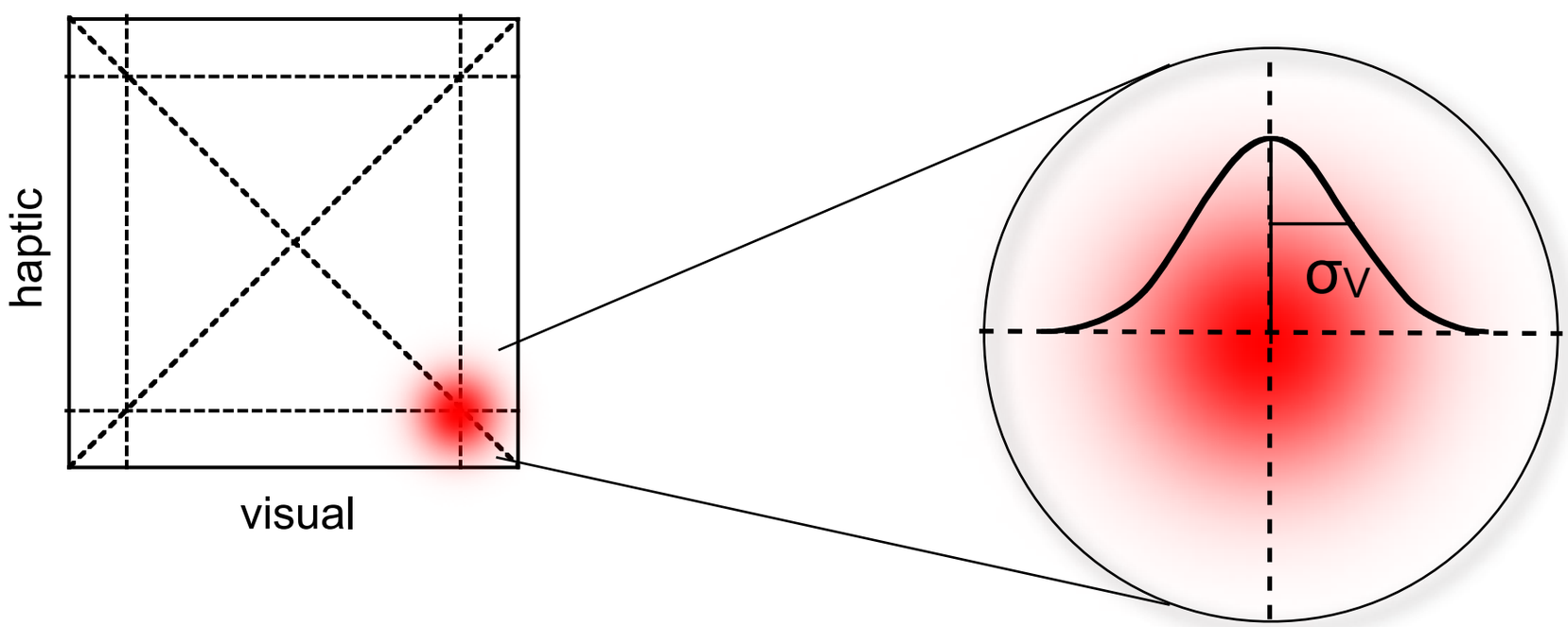
Likelihood



Ernst, Journal of Vision 2007

Modelling Integration

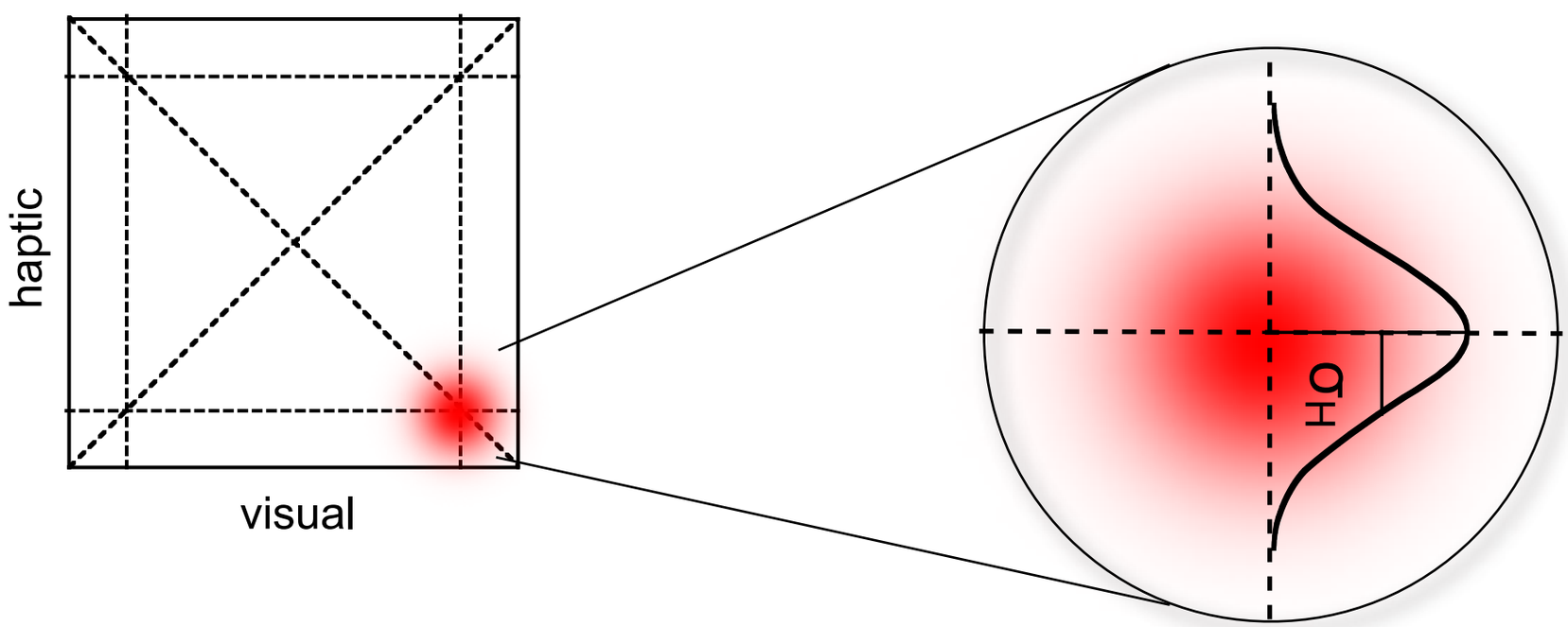
Likelihood



Ernst, Journal of Vision 2007

Modelling Integration

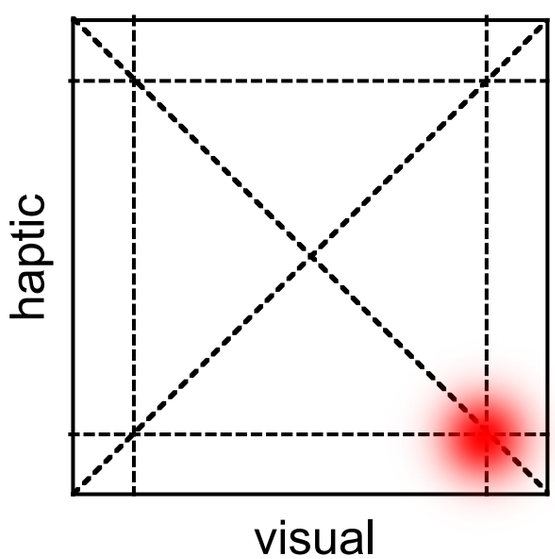
Likelihood



Ernst, Journal of Vision 2007

Modelling Integration

Likelihood



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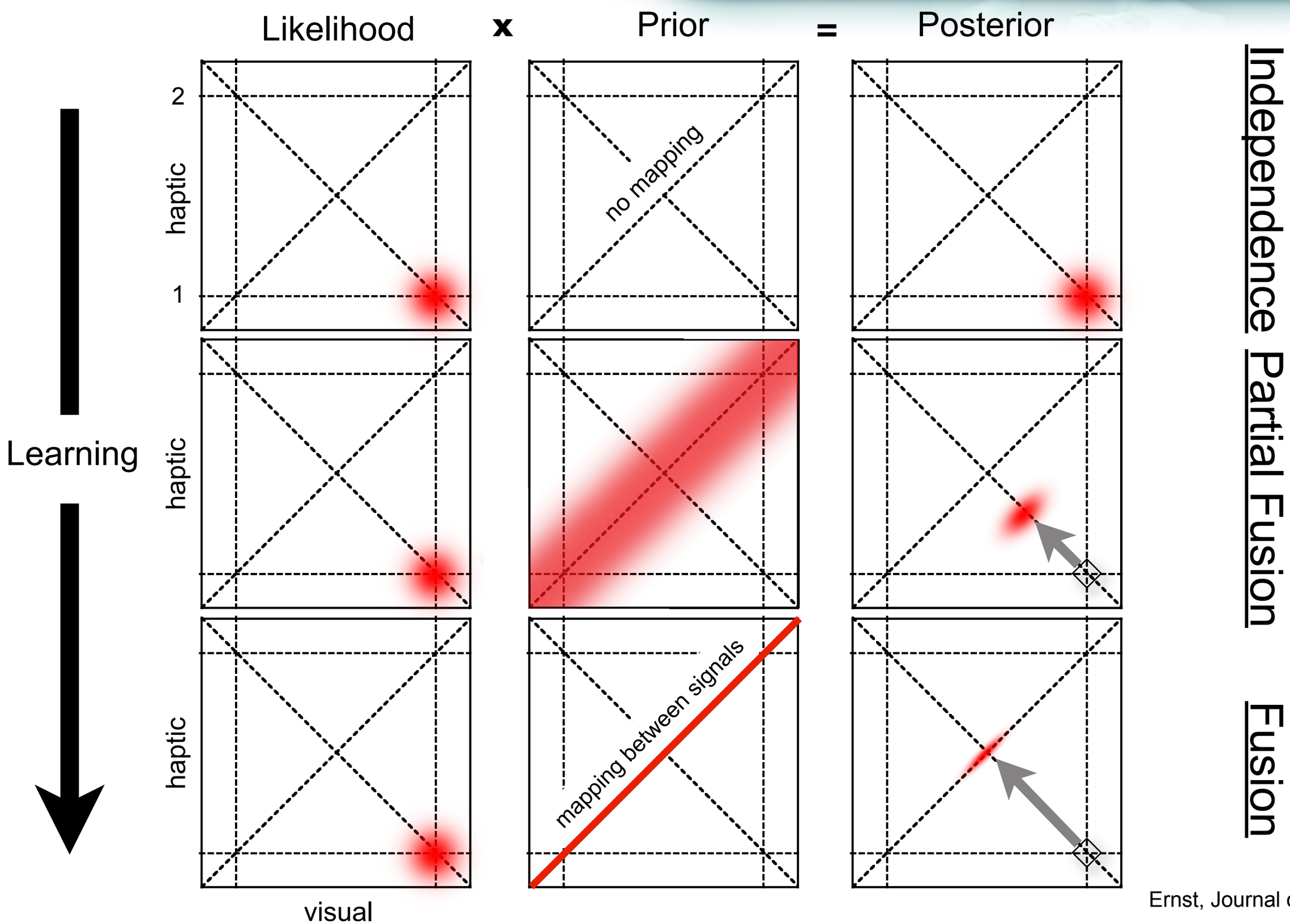
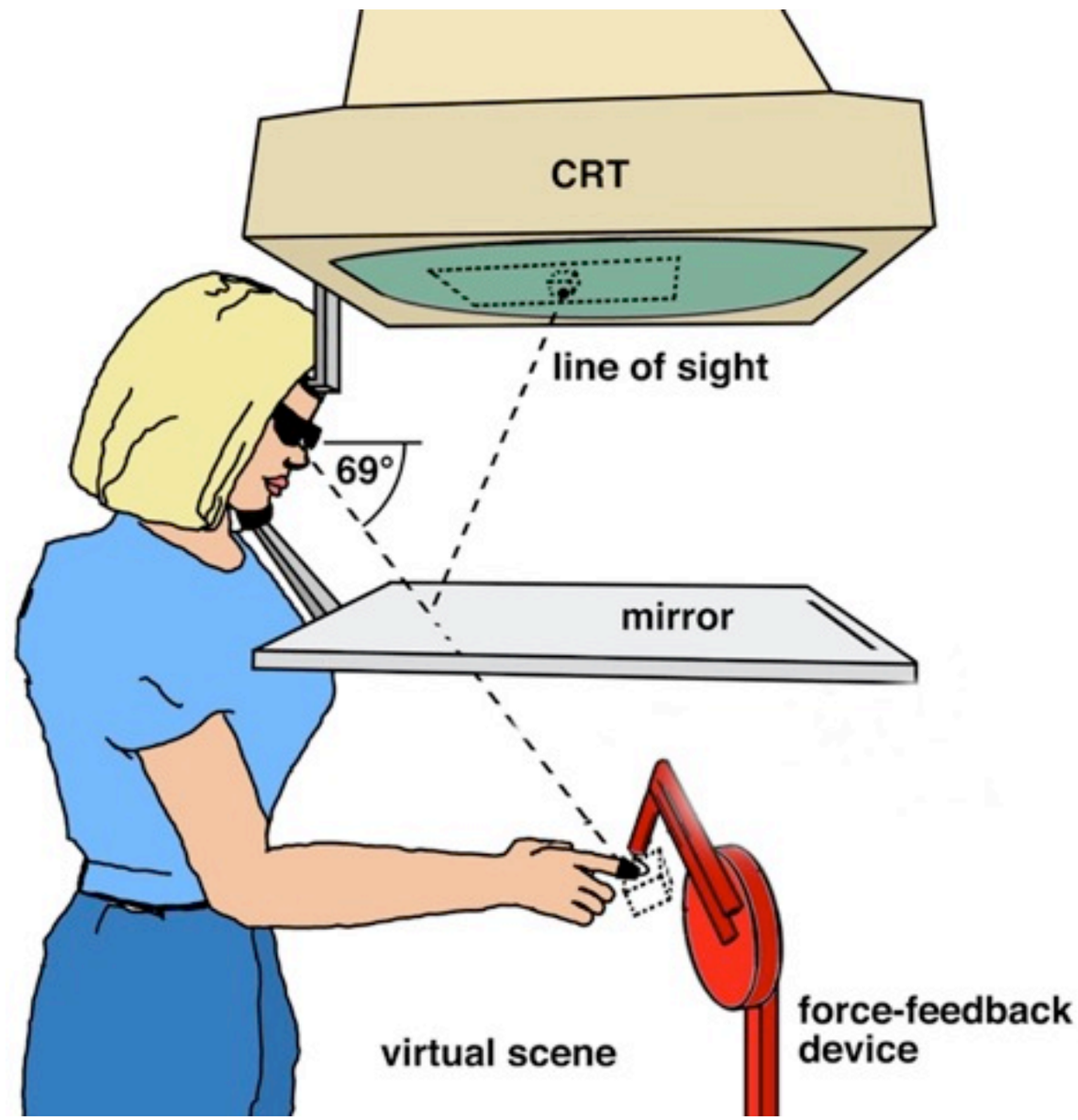
Modelling Integration



Ernst, Journal of Vision 2007

Exp. Procedure Outline

- Use **two arbitrary sensory cues** that are usually uncorrelated in the world (**luminance and stiffness**) and **train subjects** in an environment where these two cues are artificially **correlated**.
- Does training with correlated cues affect discrimination performance?
- **Two factor design**: Compare pre- vs. post-test performance for the congruent and incongruent directions (relative to training).



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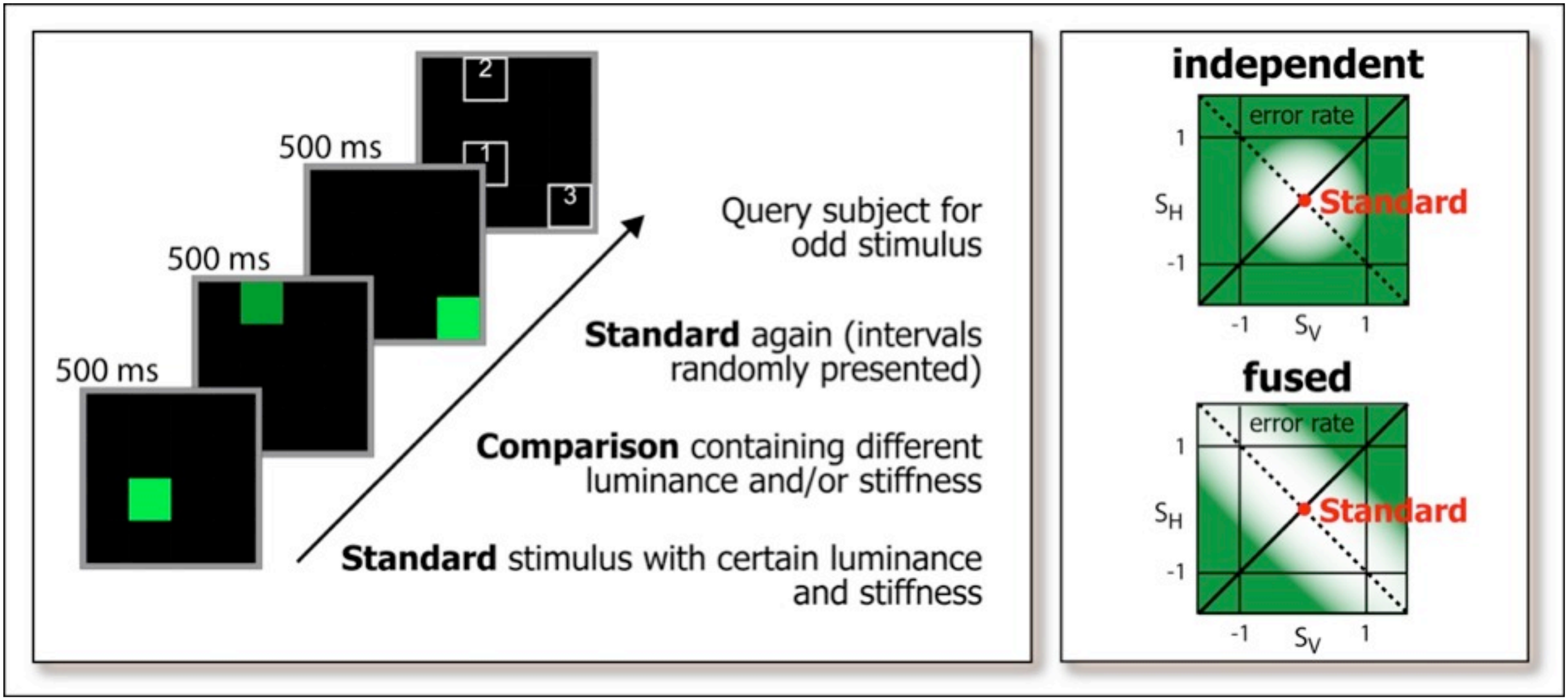
Discrimination Task

three interval oddity task **discrimination space**



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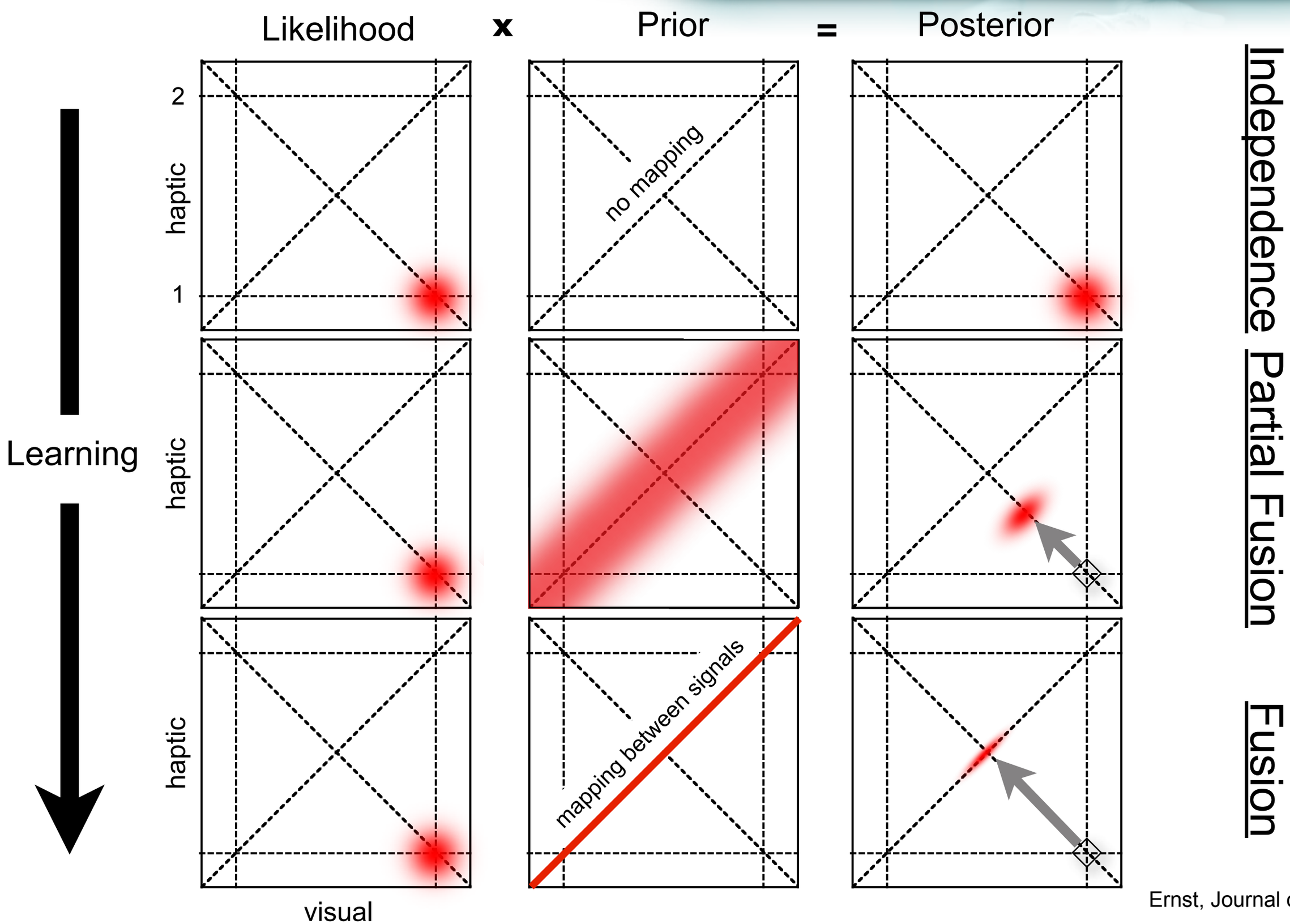

Ernst, Journal of Vision 2007

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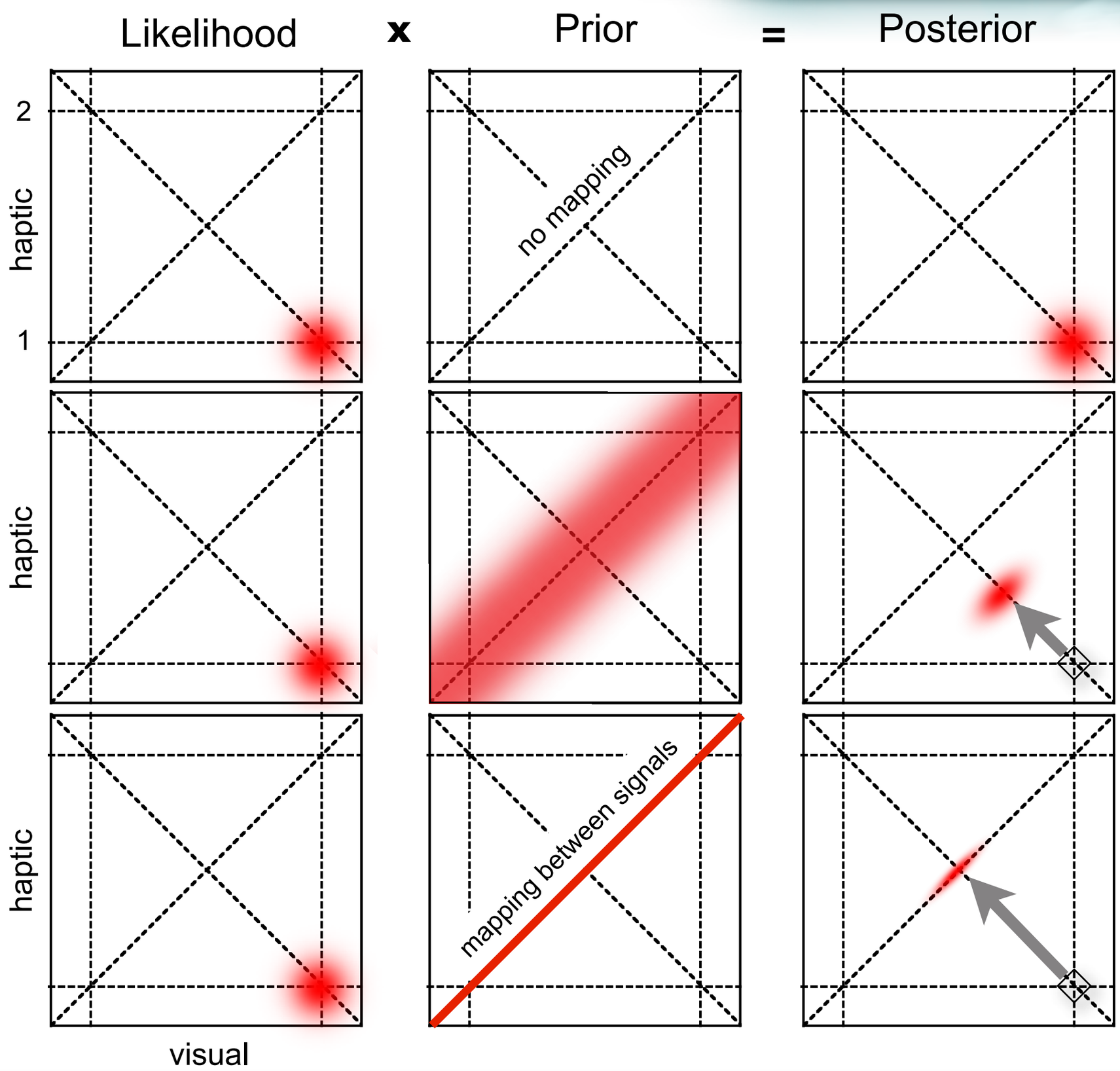
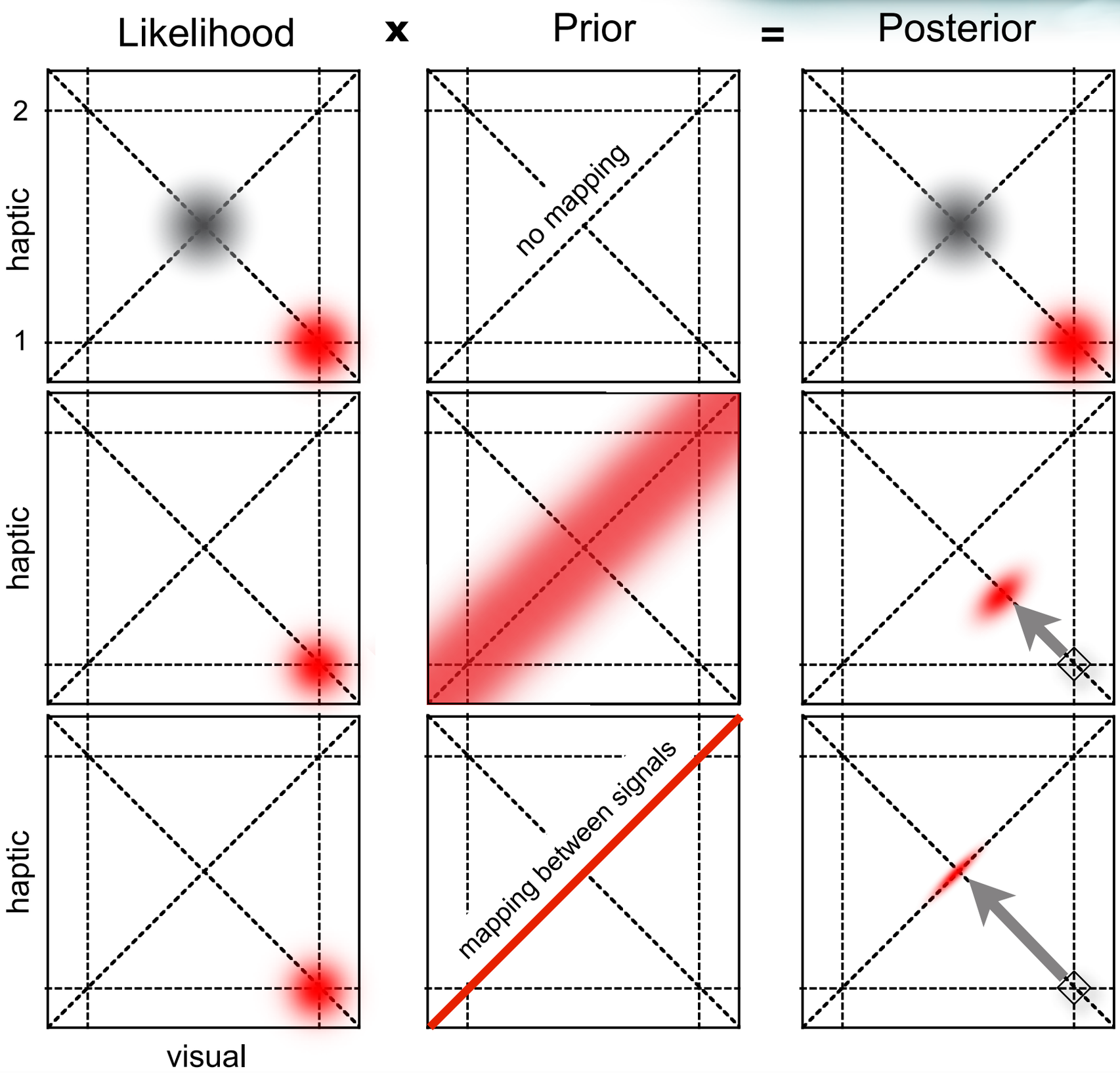


Independence Partial Fusion Fusion

Ernst, Journal of Vision 2007

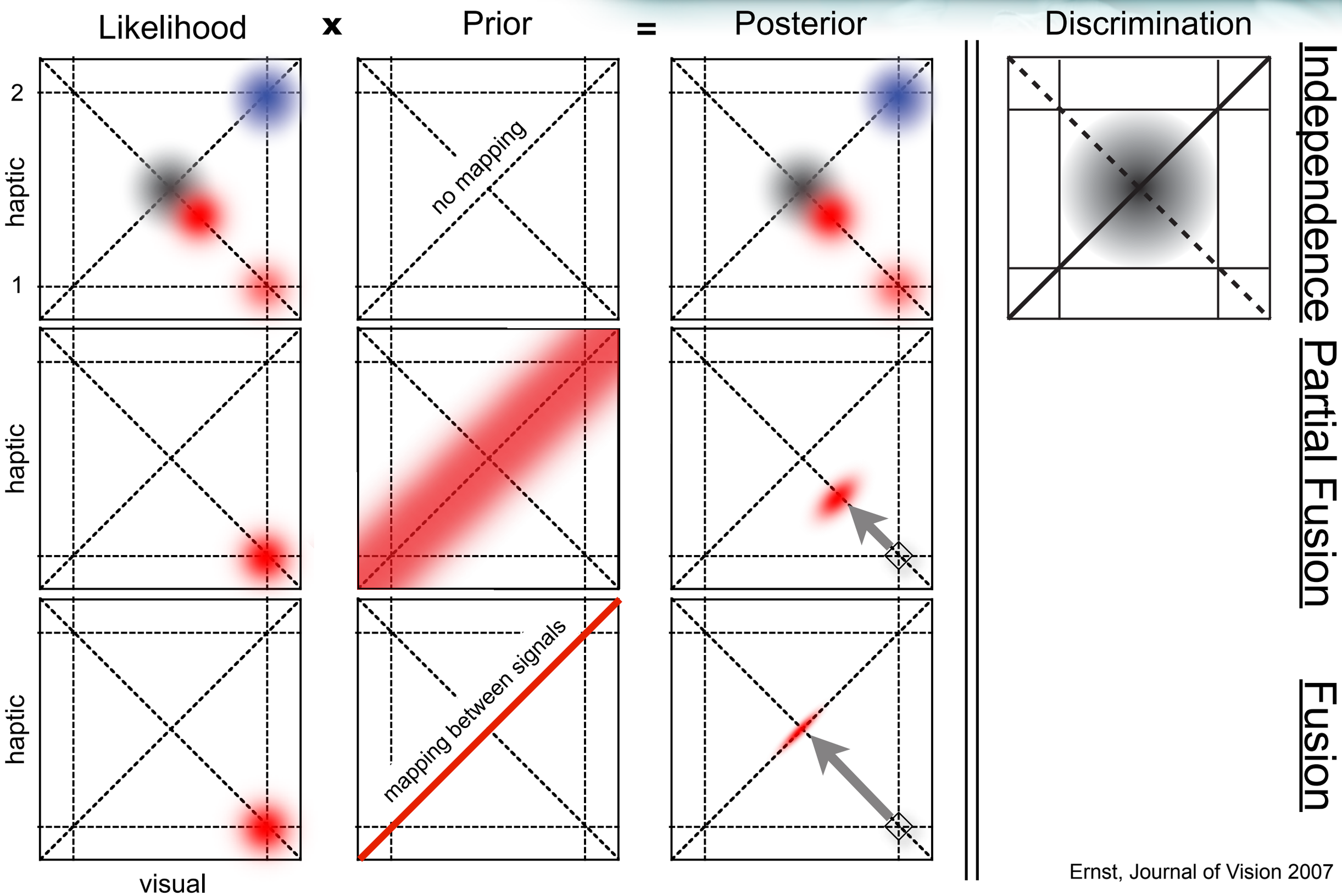
Modelling Integration



Independence Partial Fusion Fusion

Ernst, Journal of Vision 2007

Modelling Integration



Ernst, Journal of Vision 2007

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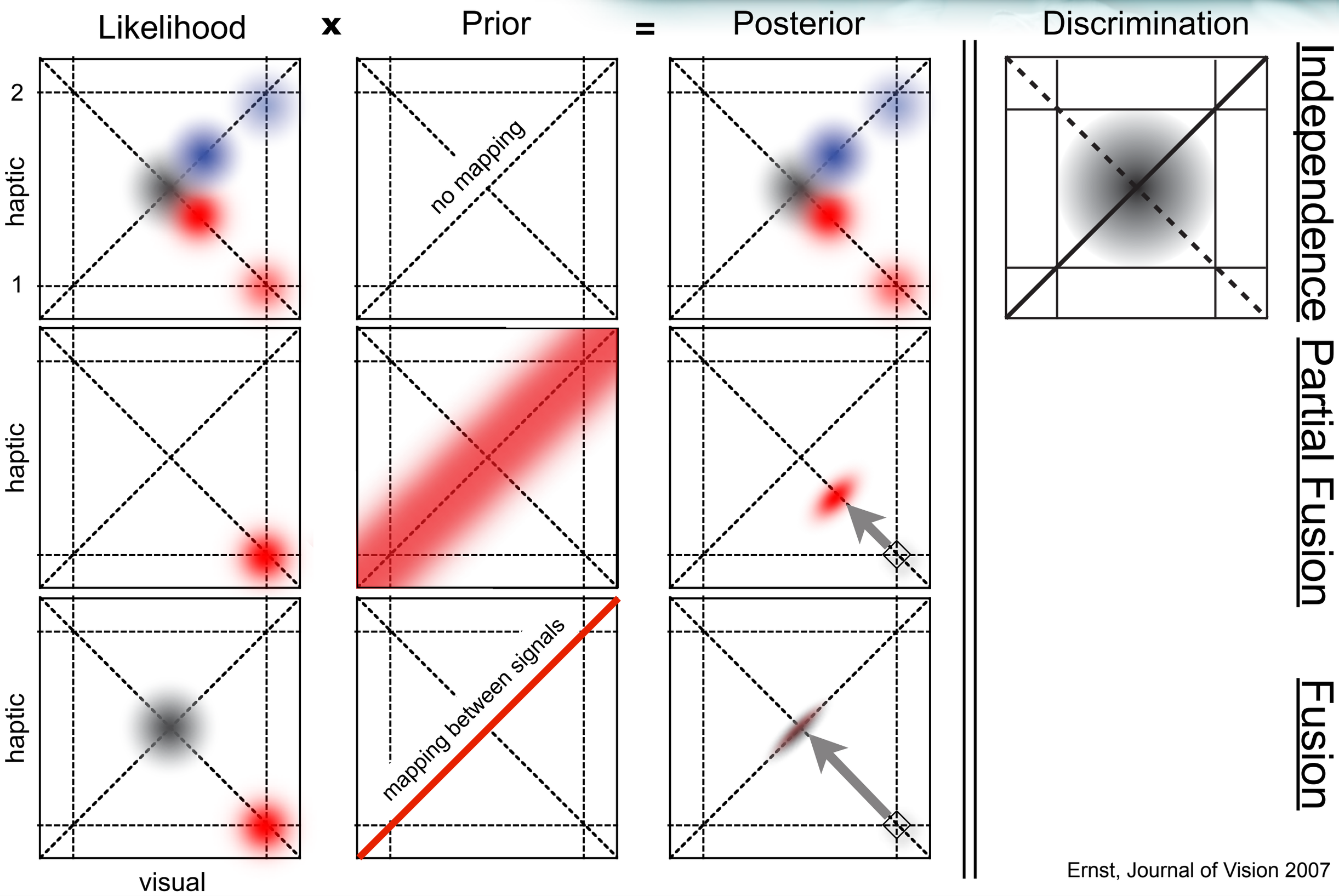

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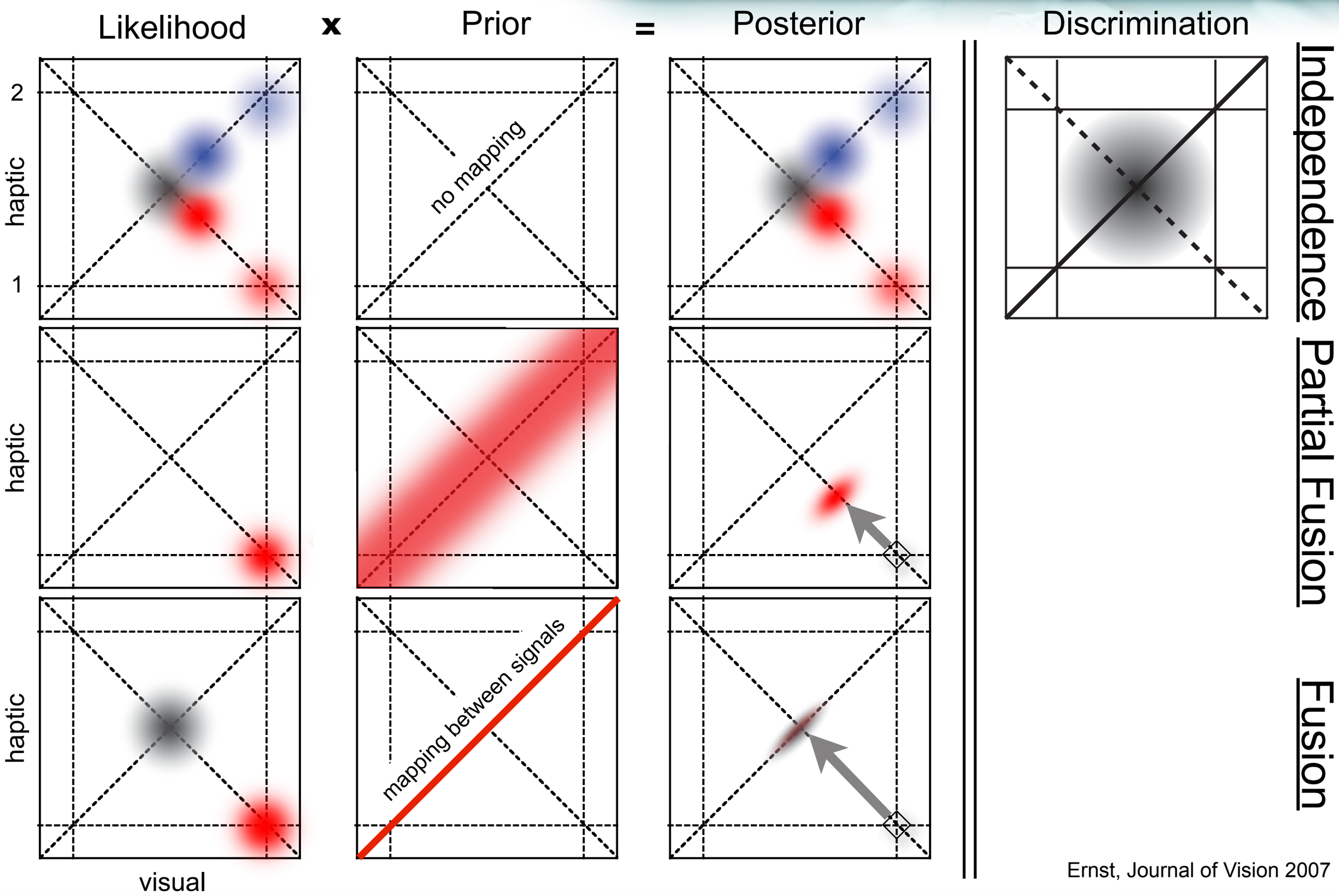

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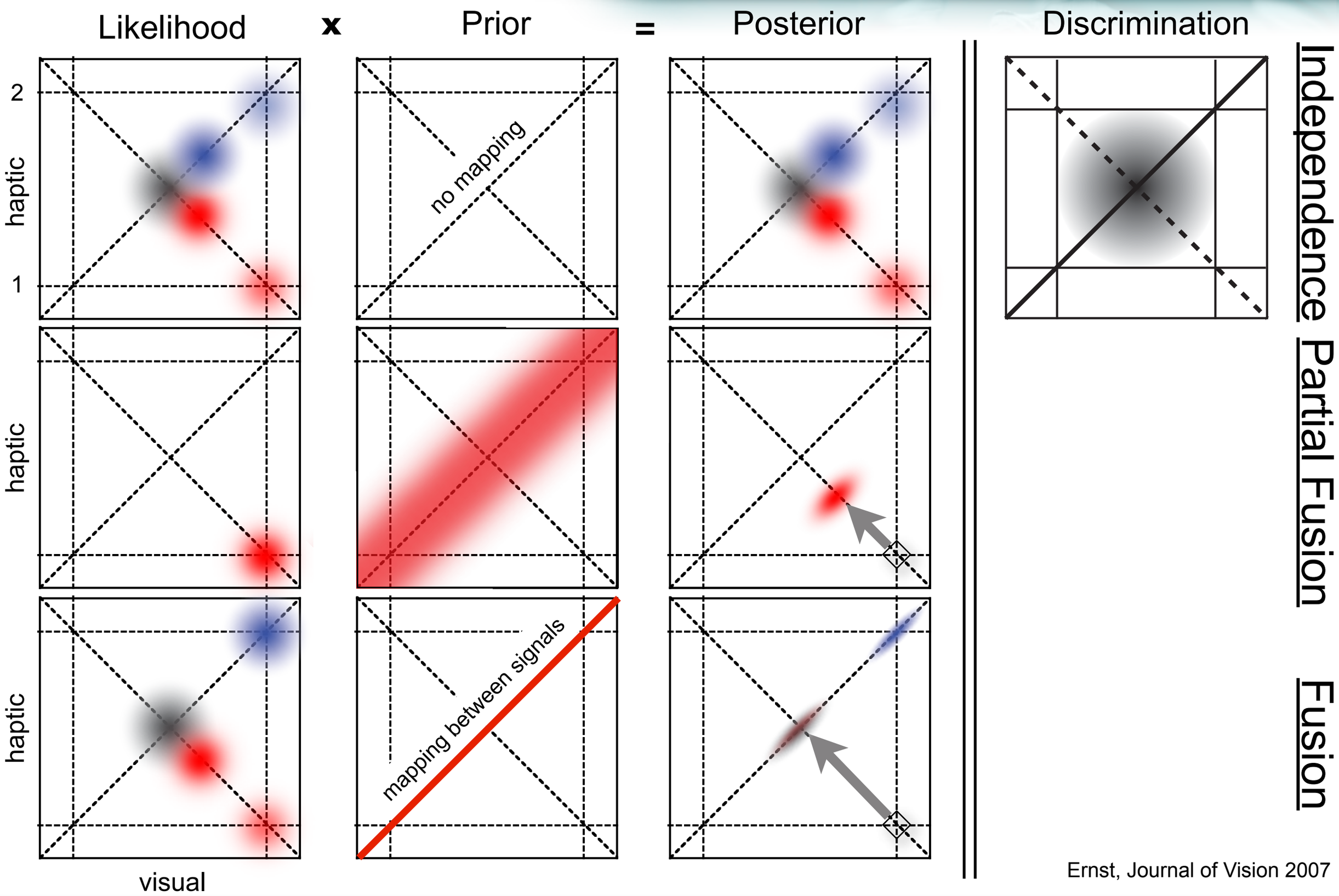

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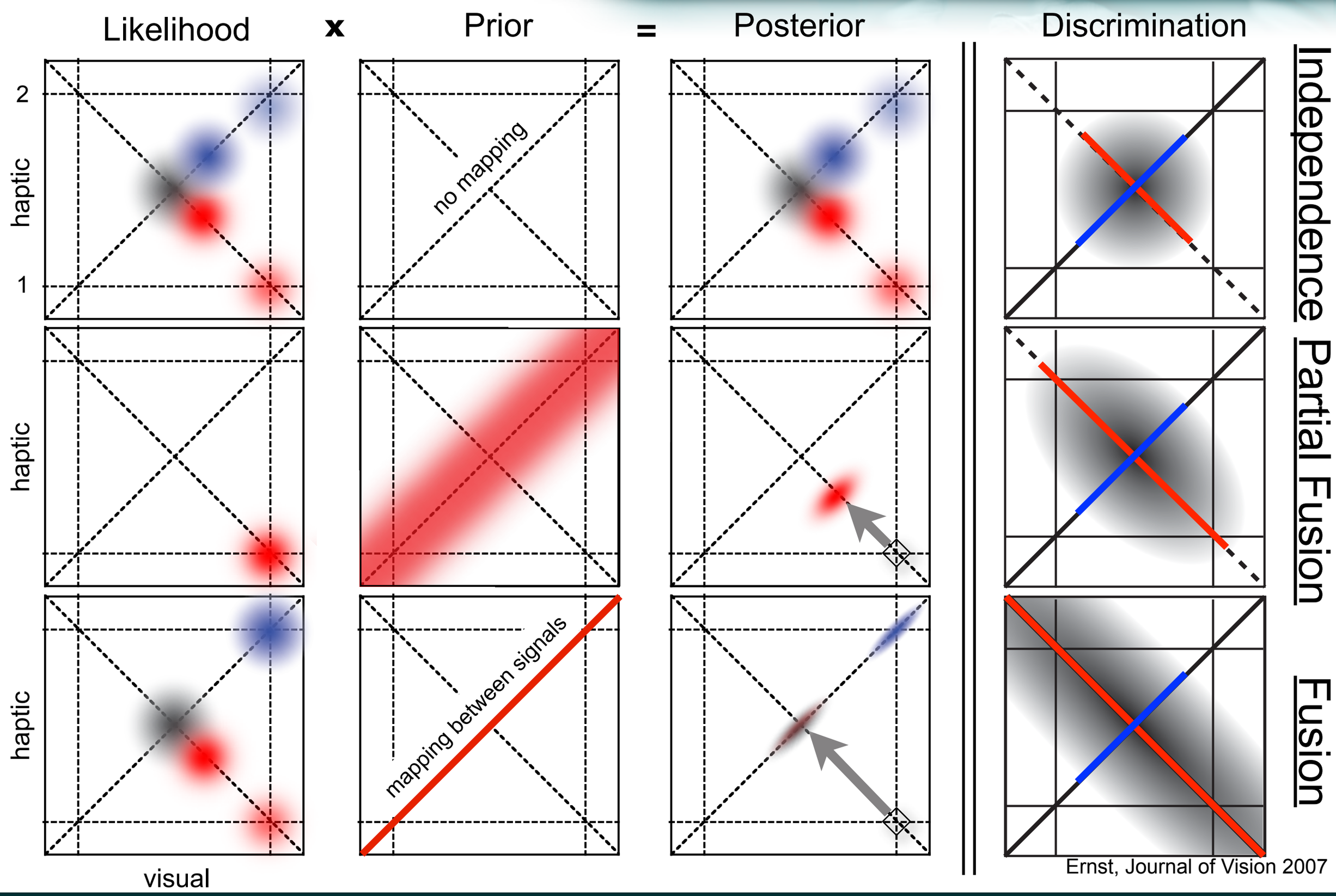

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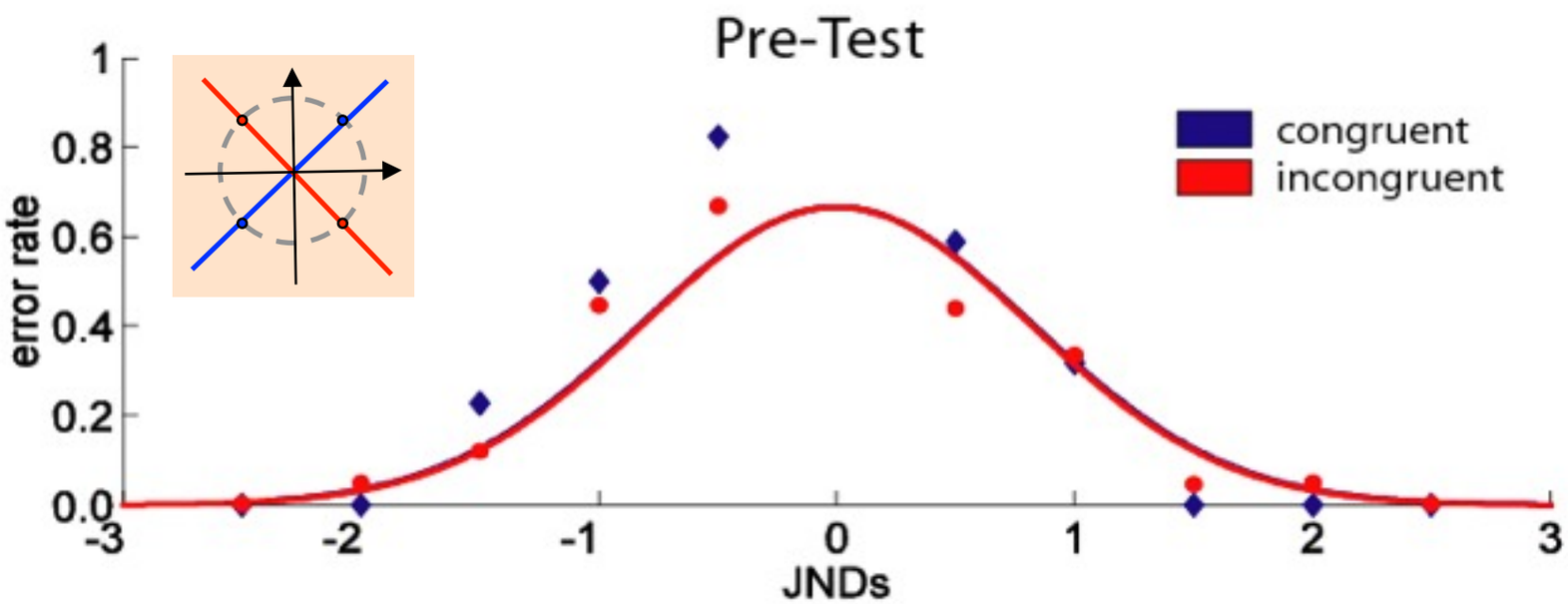
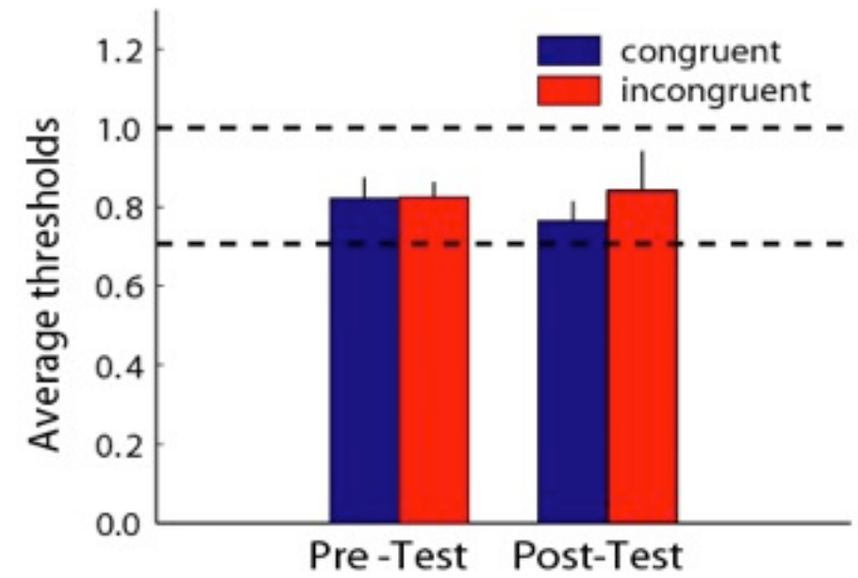
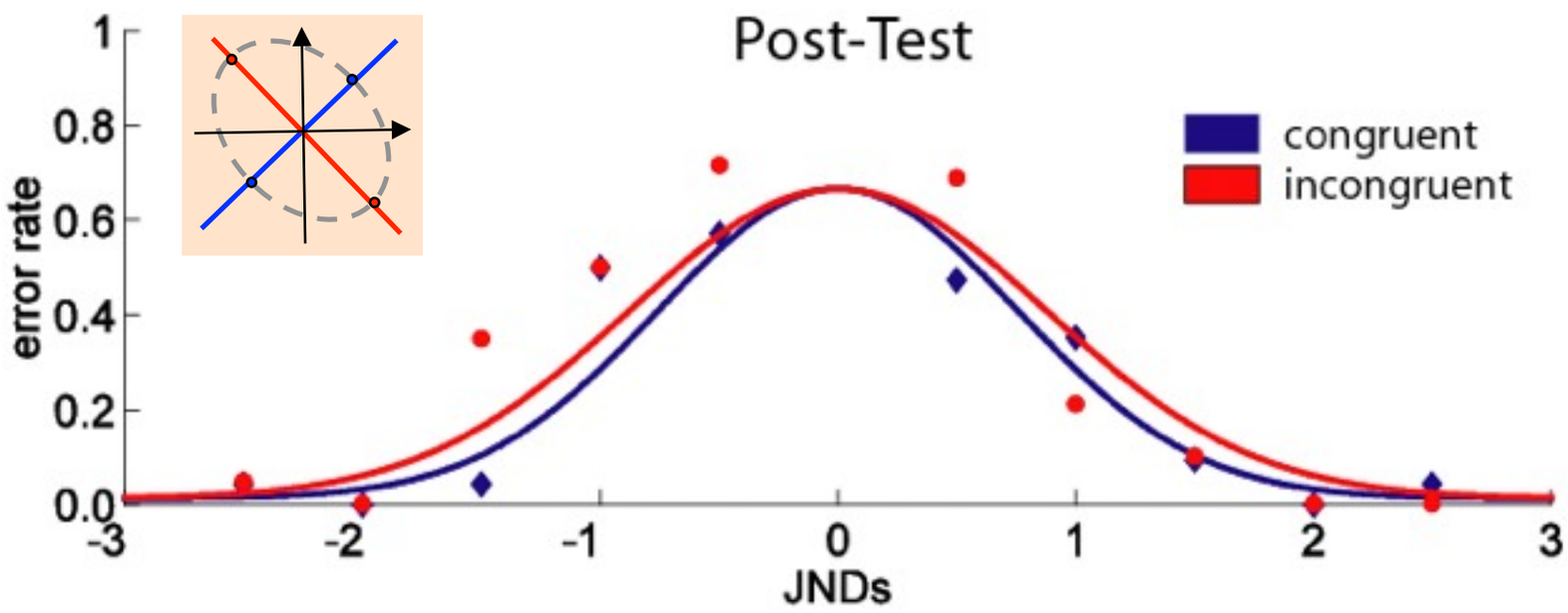
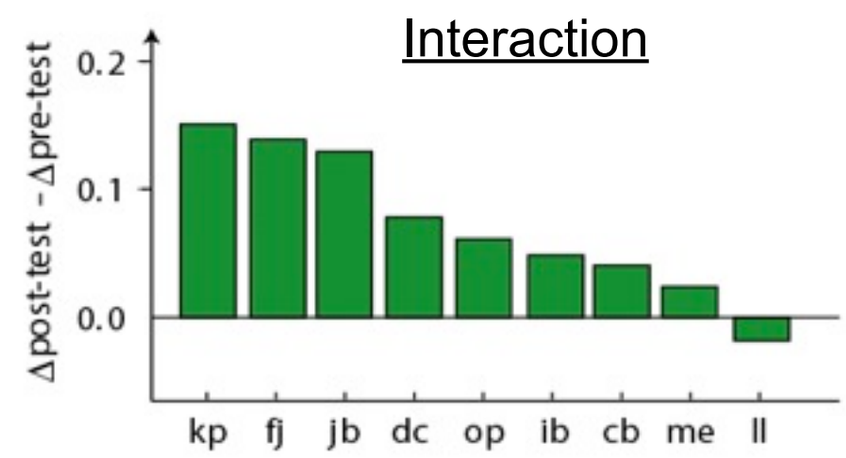
Pre- & Post-Test Discrimination









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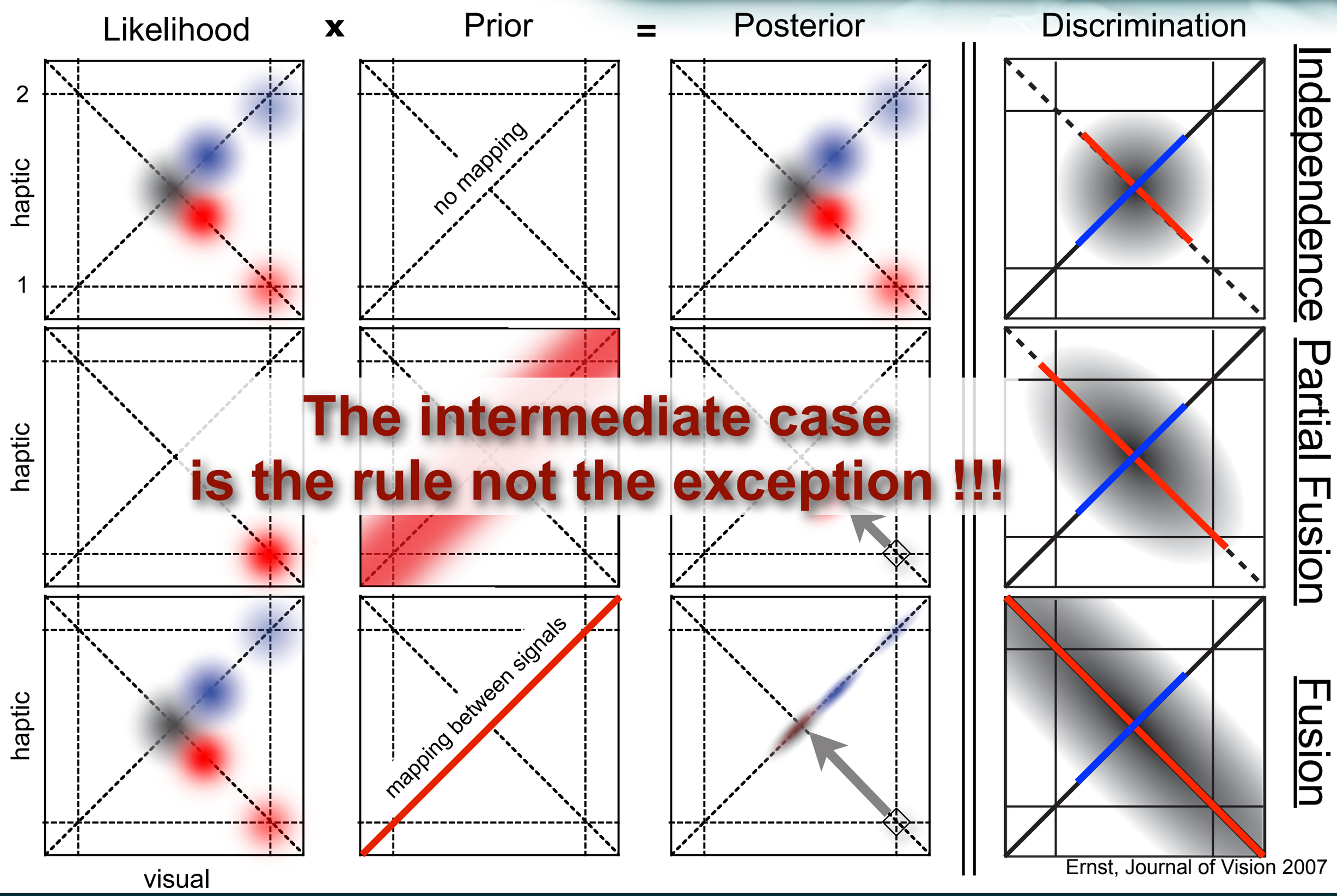
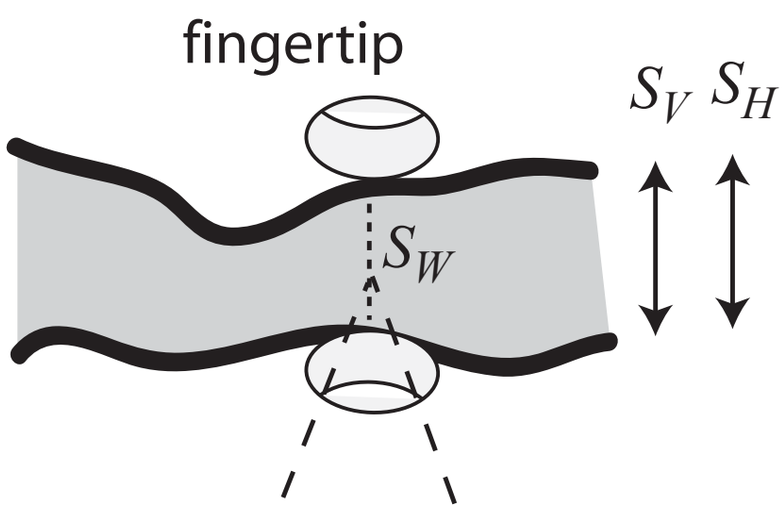
Modelling Integration

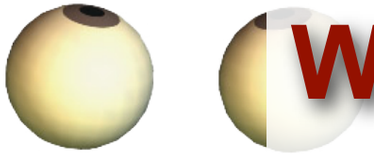


The intermediate case is the rule not the exception !!!

Ernst, Journal of Vision 2007

Co-occurrence Statistics

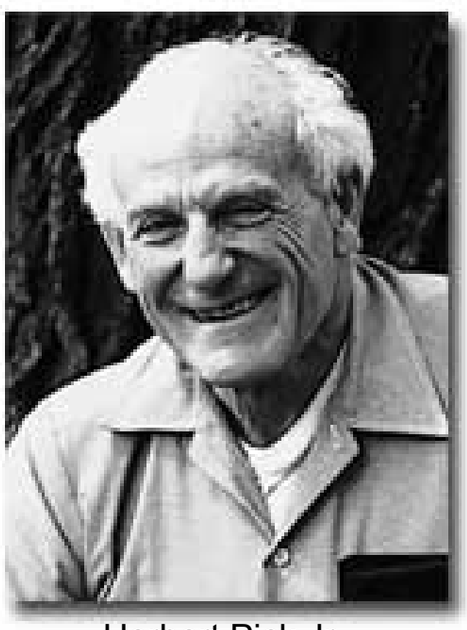




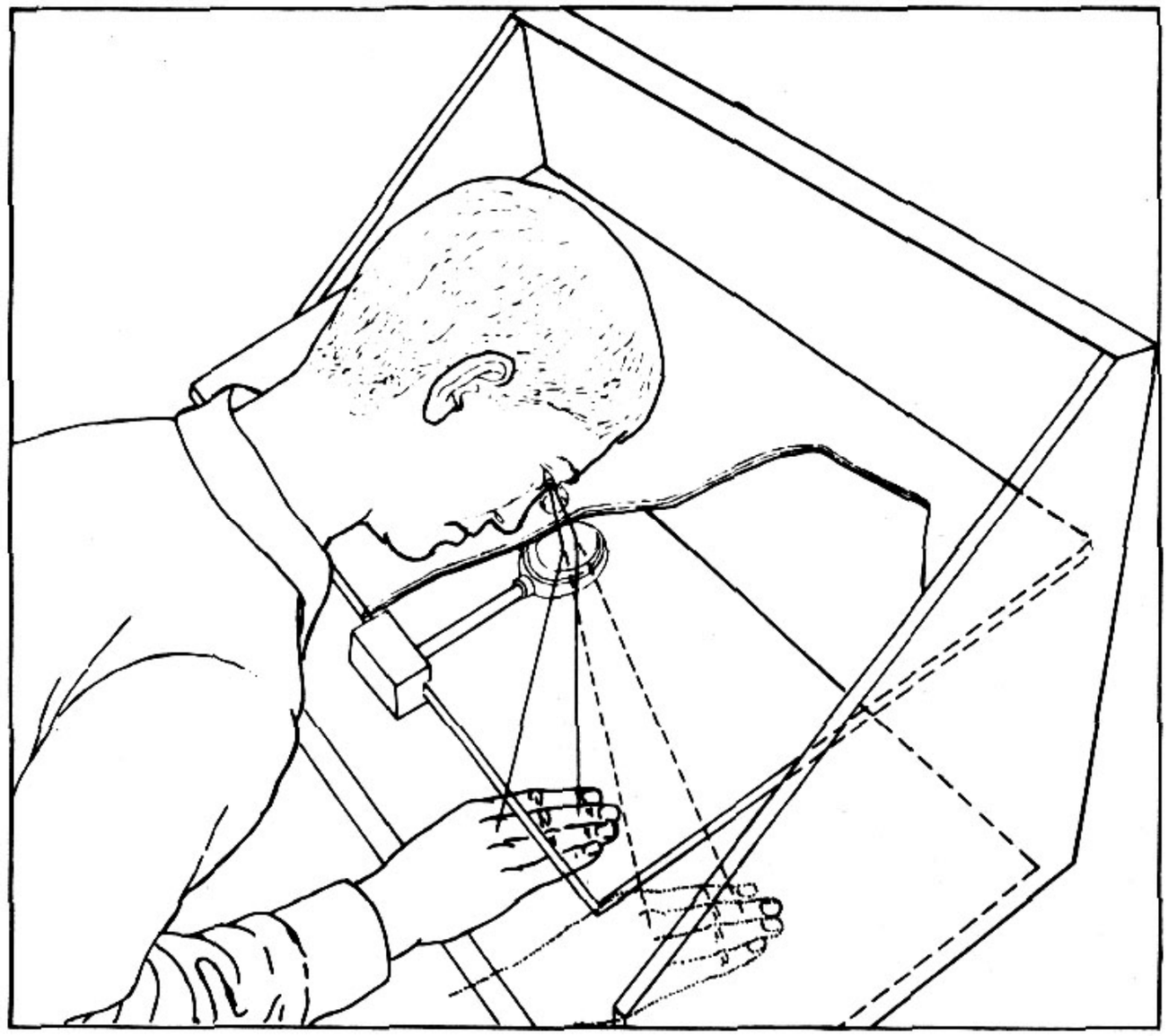
What if a conflict is persistent, i.e, signals are biased?

Visuomotor Adaptation

Hermann von Helmholtz
(1821-1894)



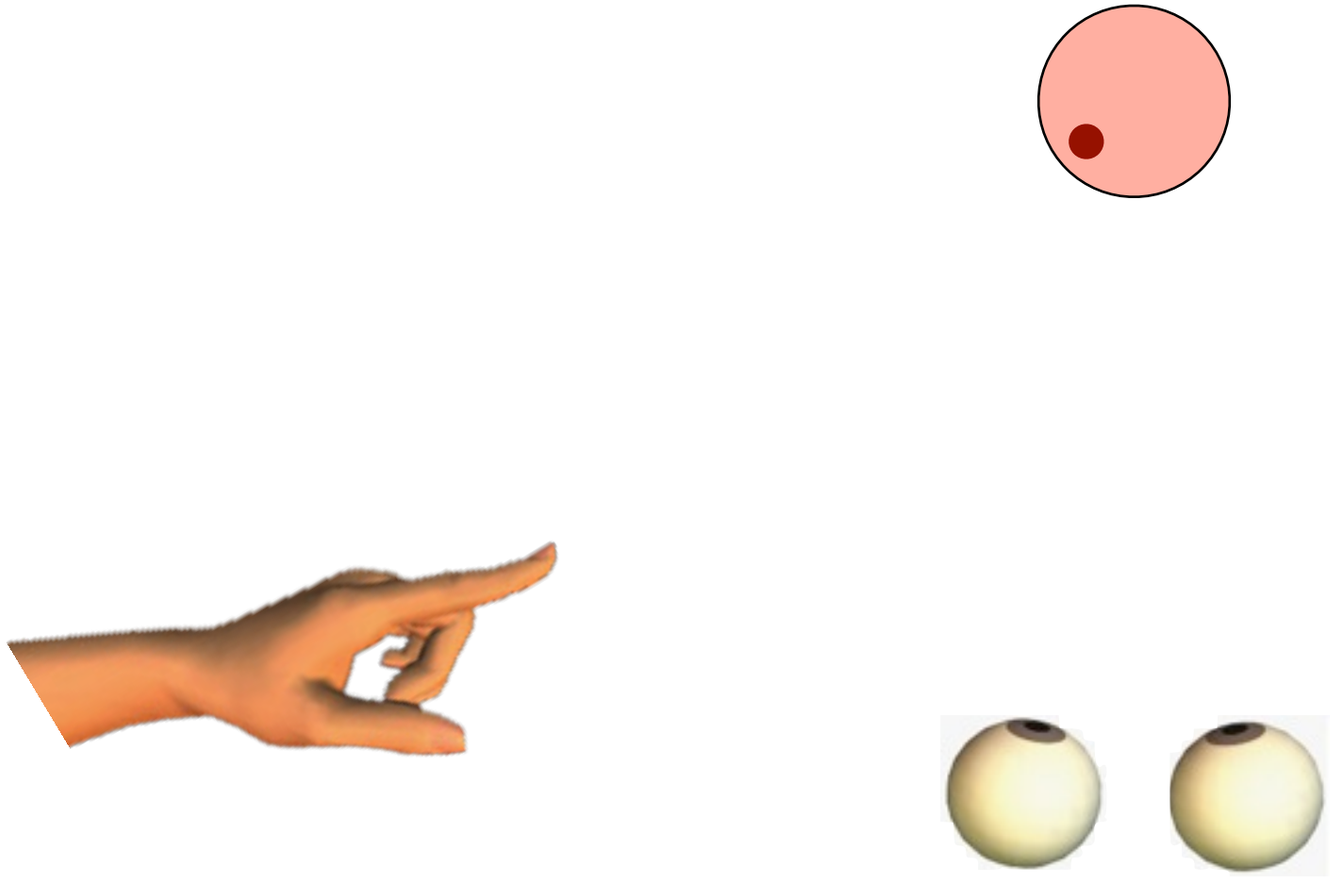
Herbert Pick Jr.



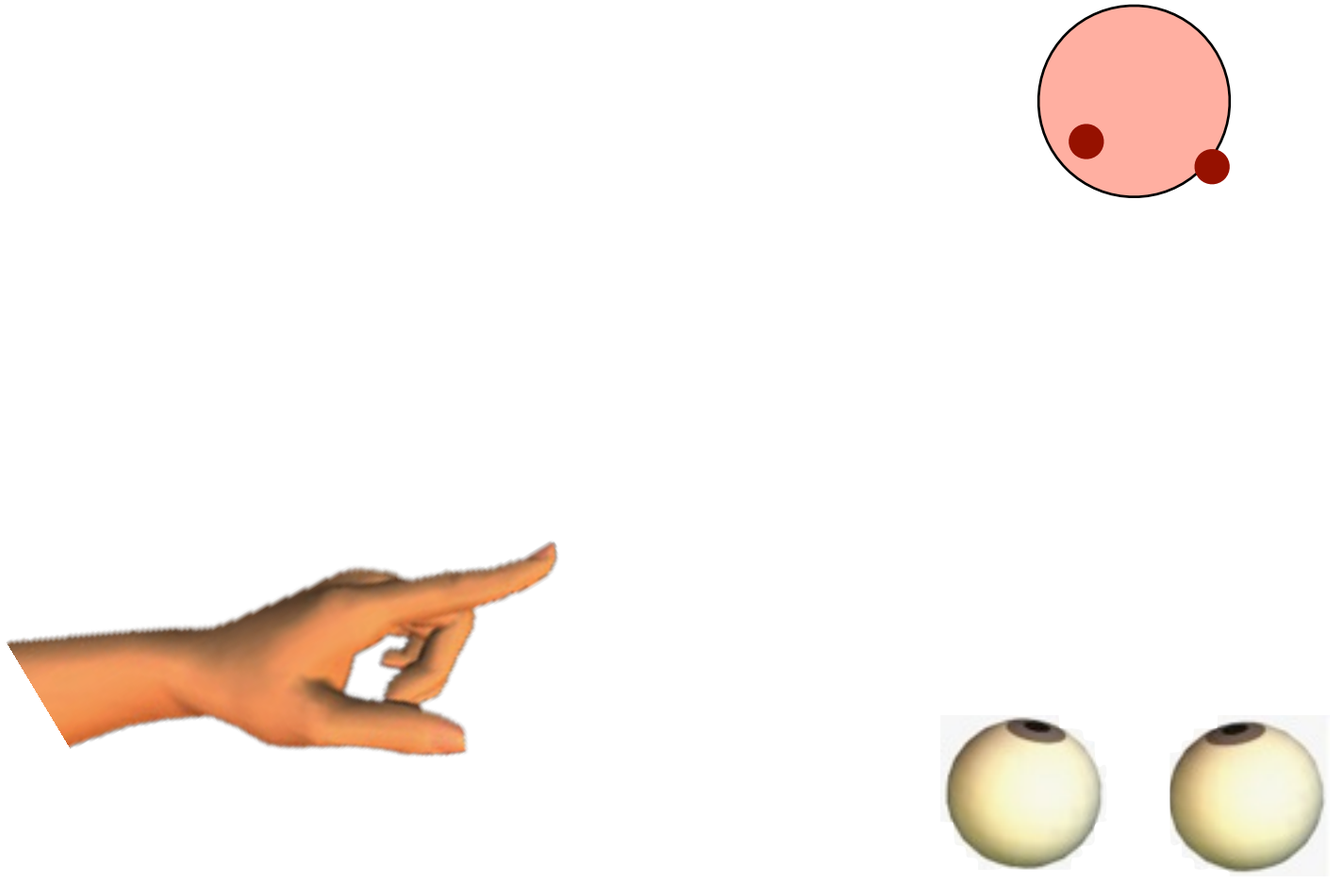
Seeing the hand through a distortion lens

- Visual and proprioceptive representation in conflict!
- How to adapt this systematic error?

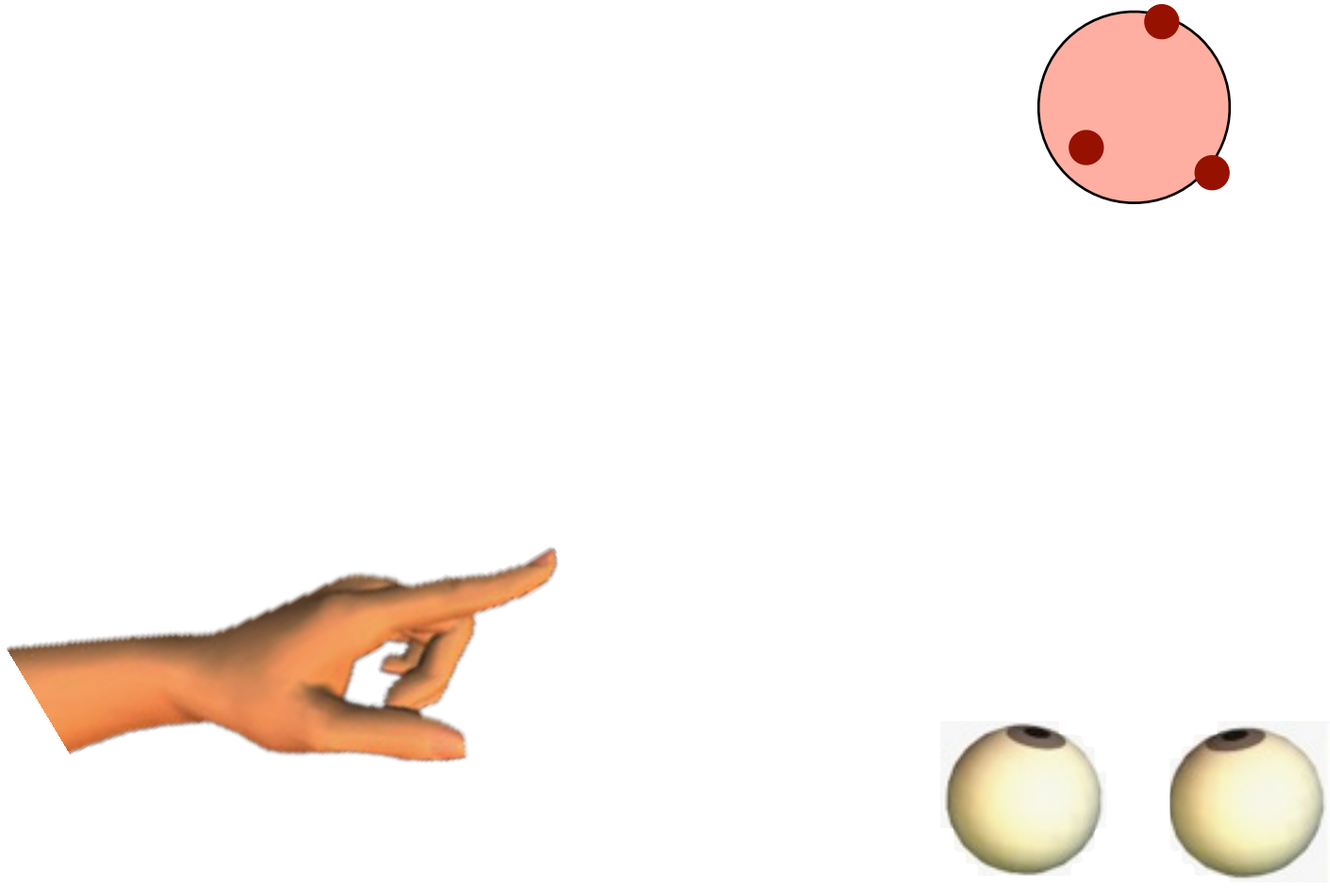
Pointing to Target



Pointing to Target



Pointing to Target



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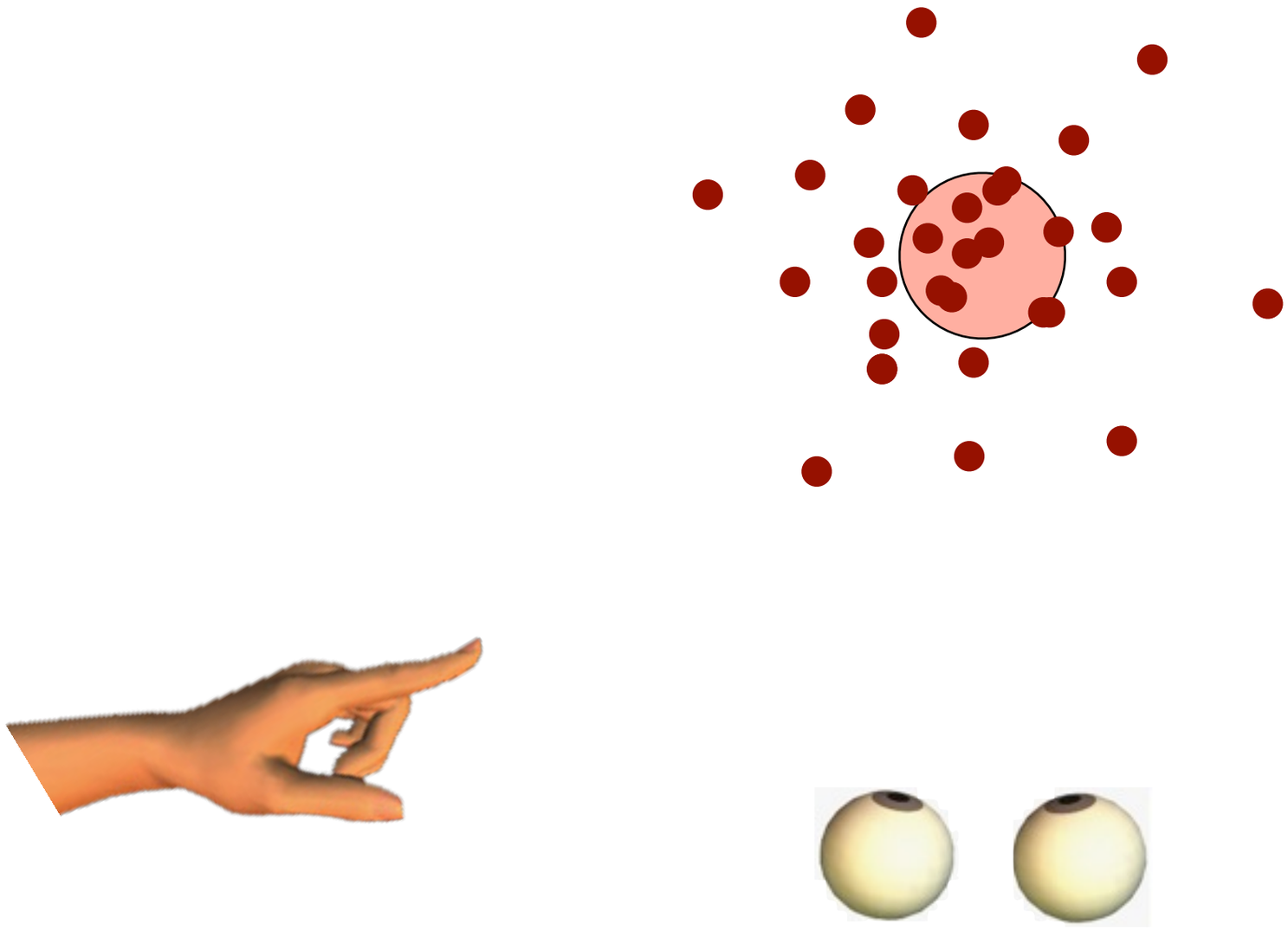
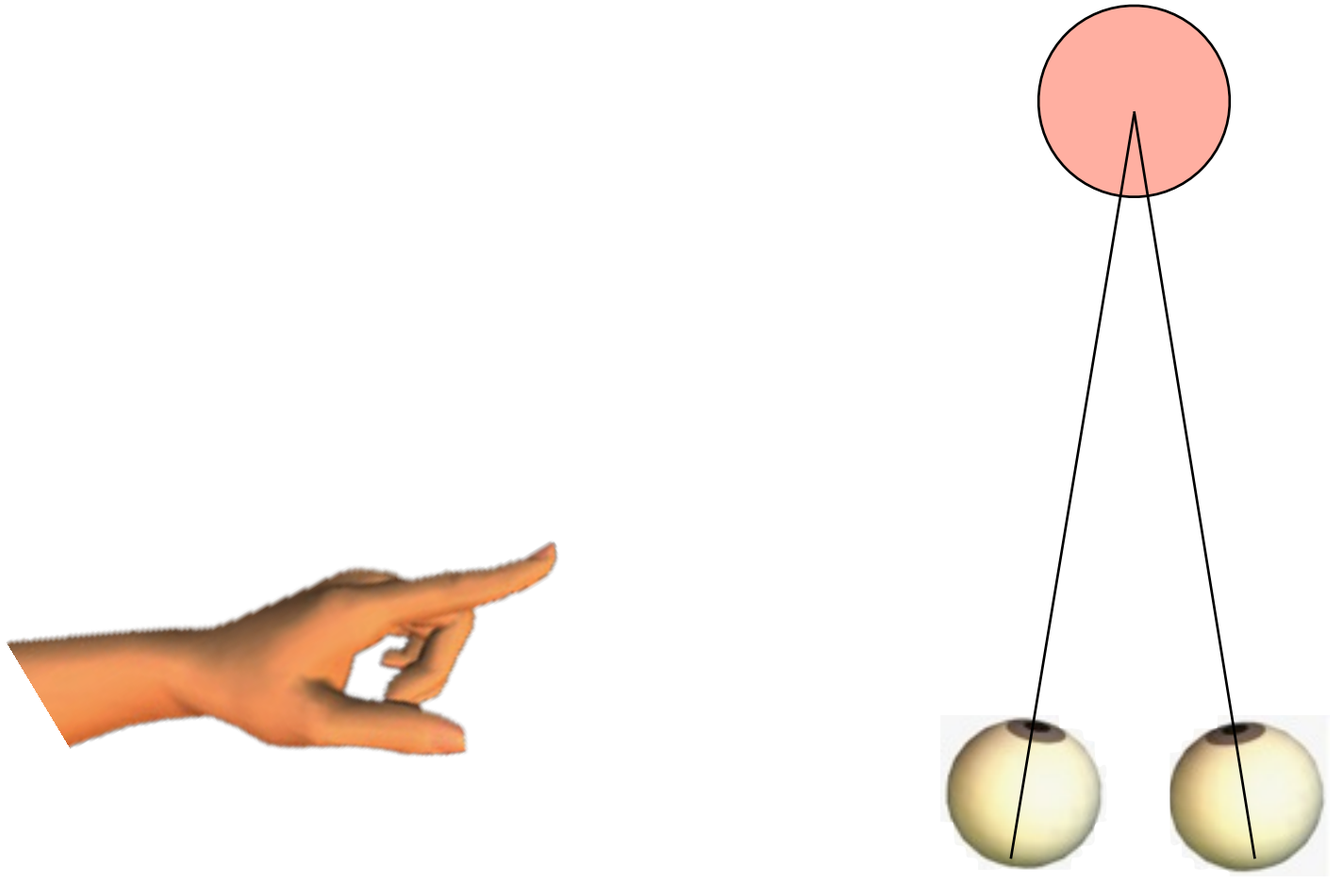
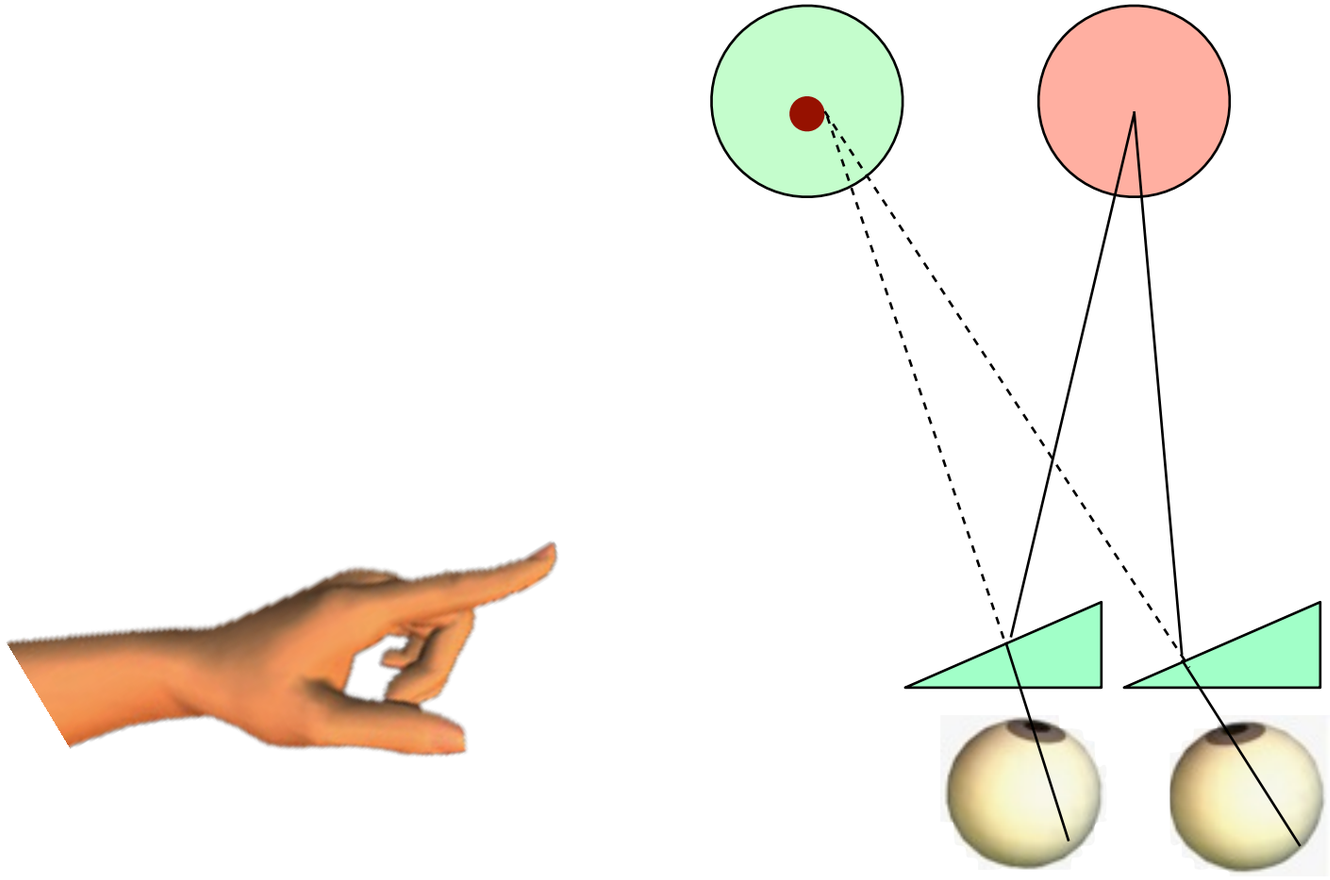


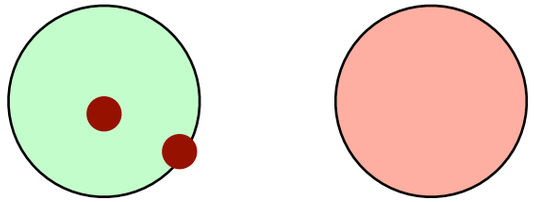
Pointing to Target

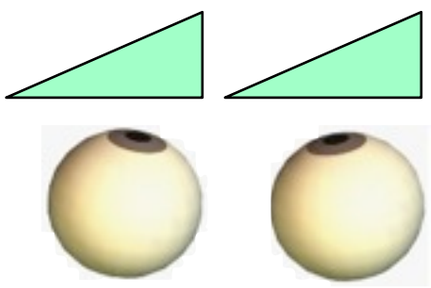


Pointing with Prism Shift

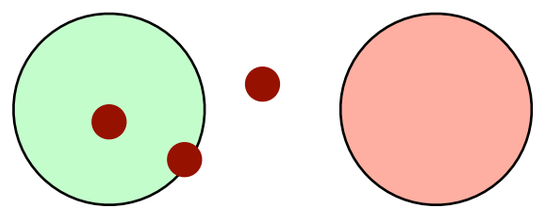


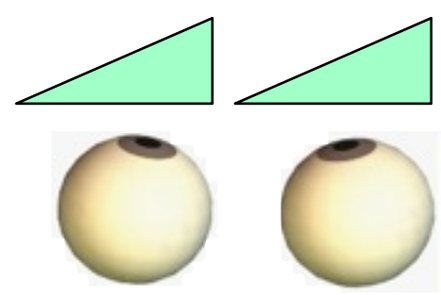
Pointing with Prism Shift



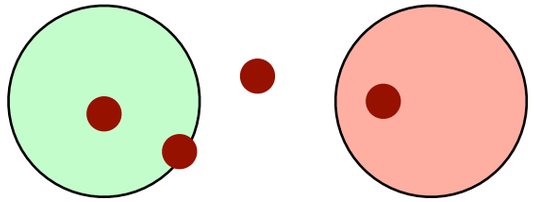


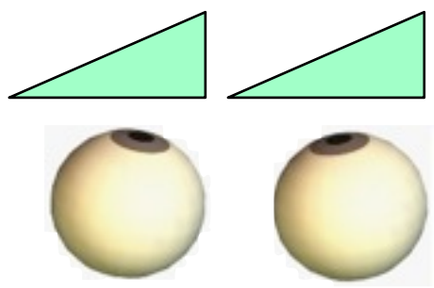
Pointing with Prism Shift



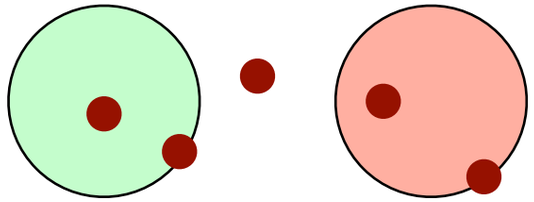


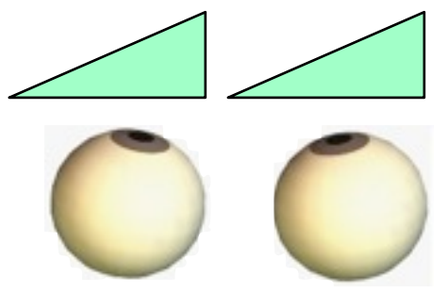
Pointing with Prism Shift



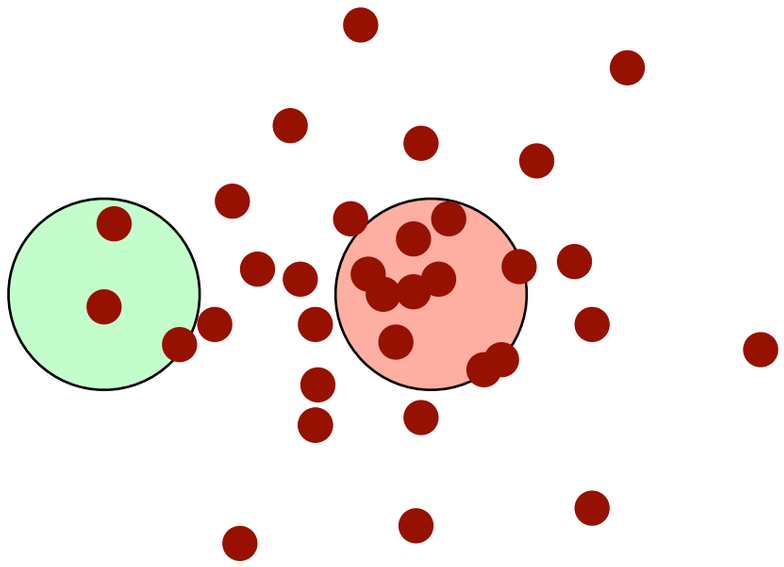


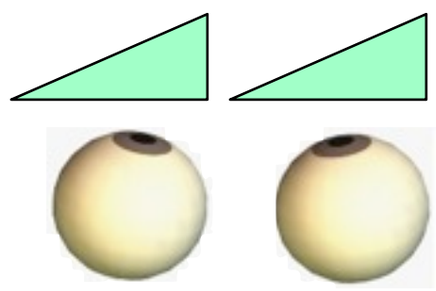
Pointing with Prism Shift



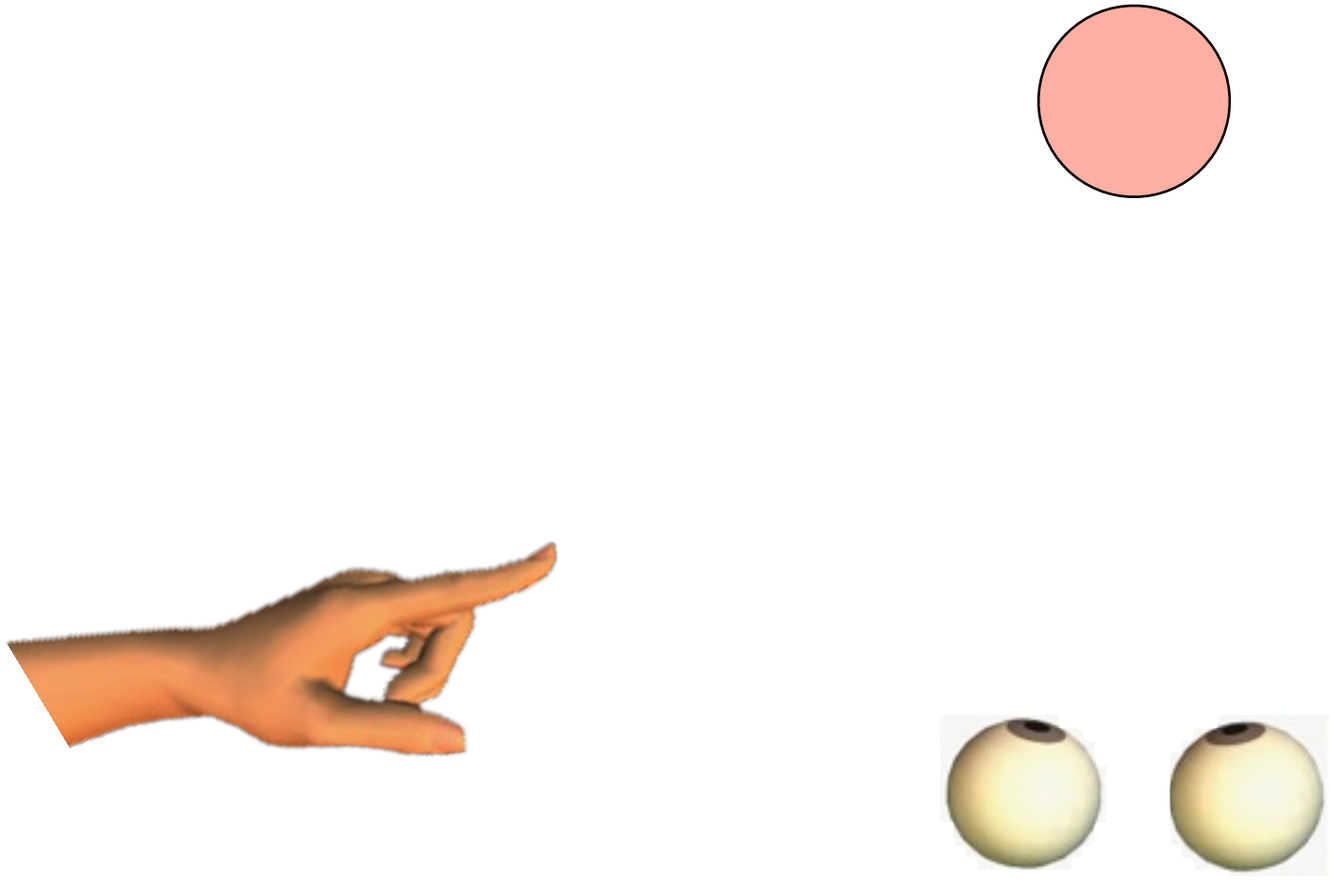


Pointing with Prism Shift

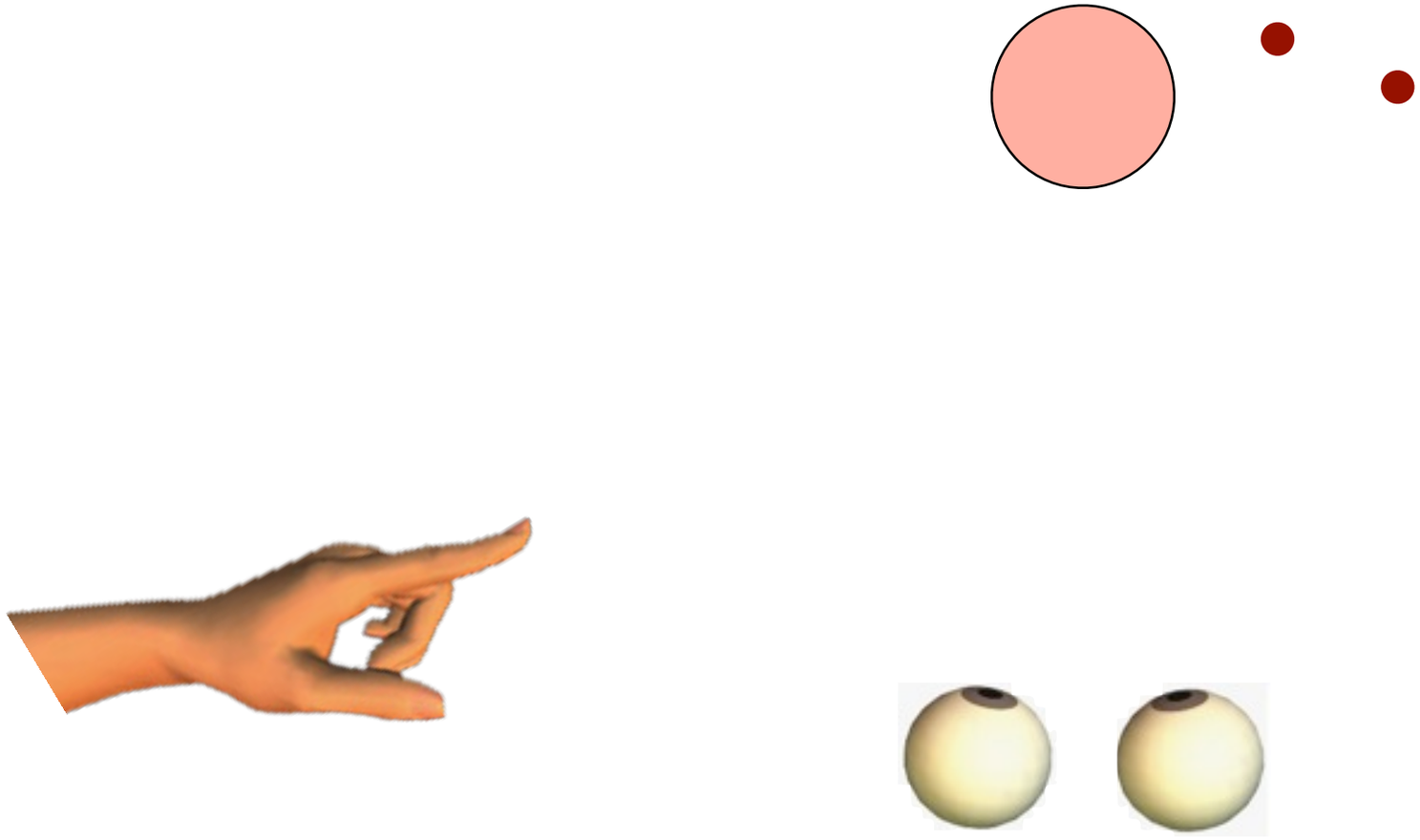




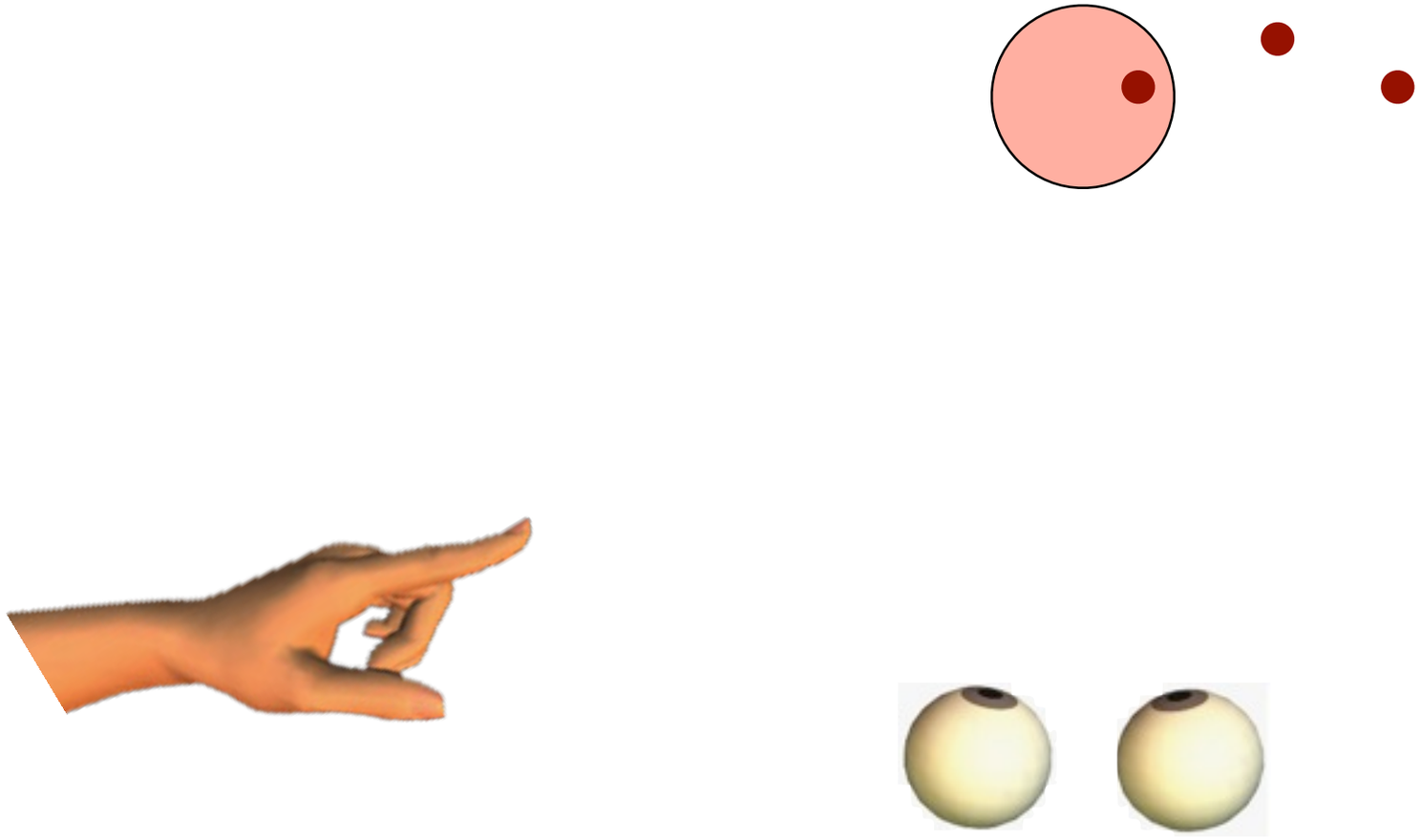
Prism Aftereffect



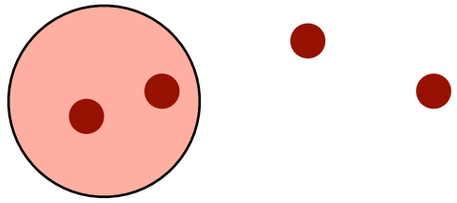
Prism Aftereffect



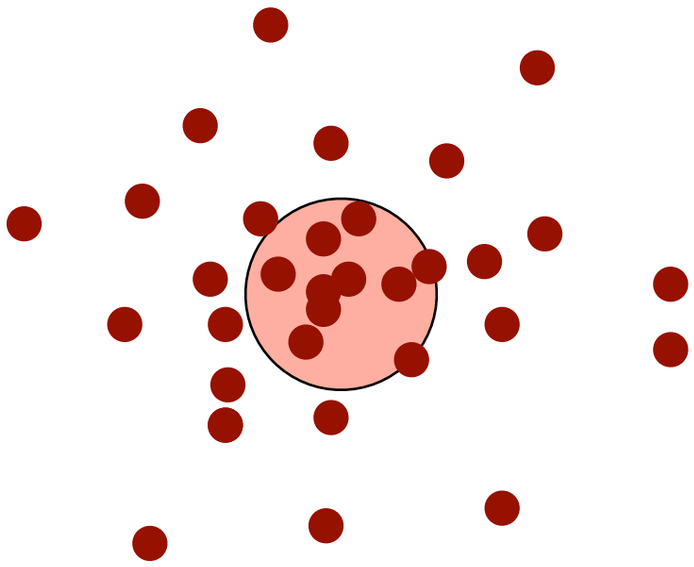
Prism Aftereffect



Prism Aftereffect

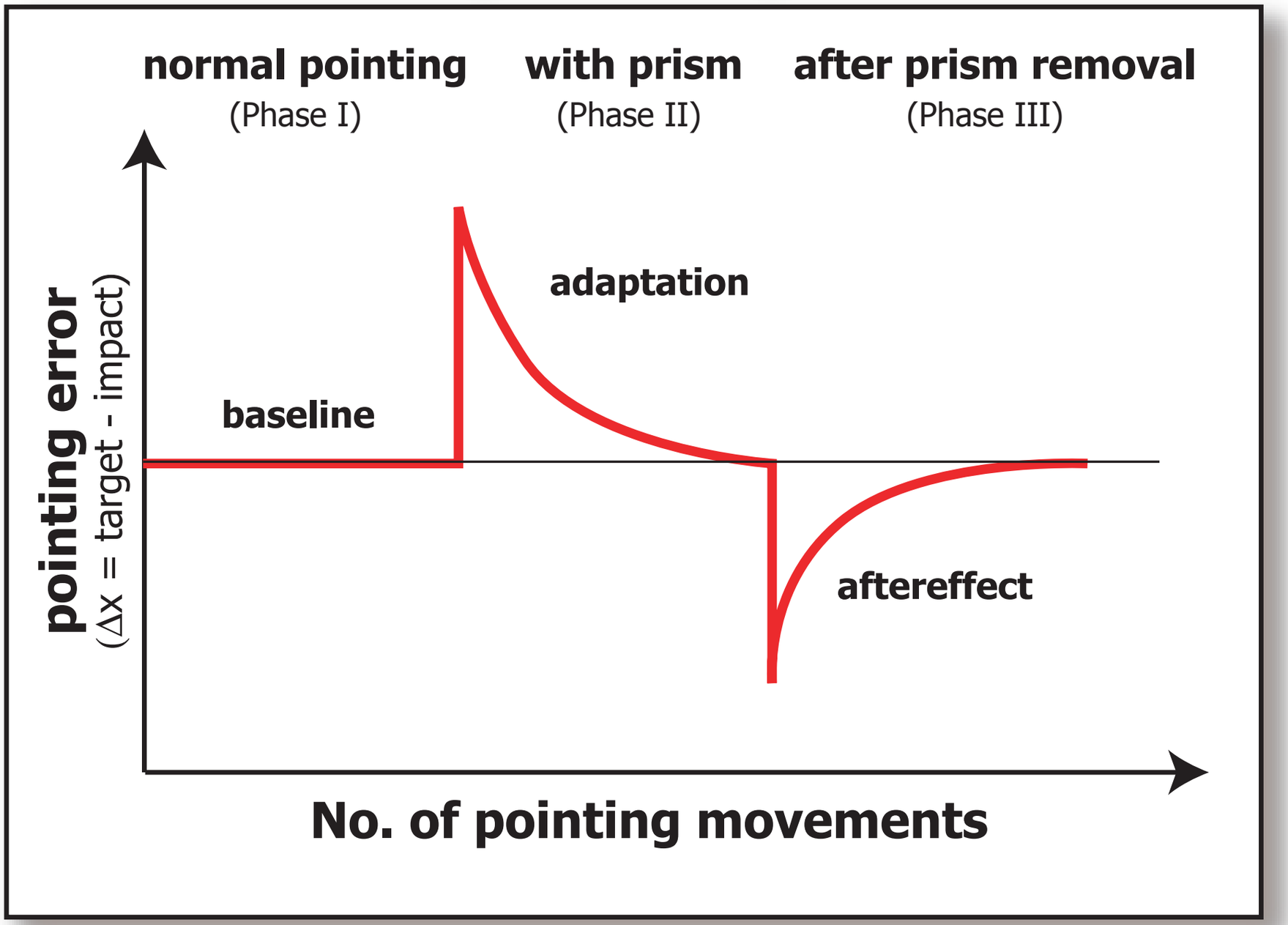


Prism Aftereffect



Visuomotor Adaptation

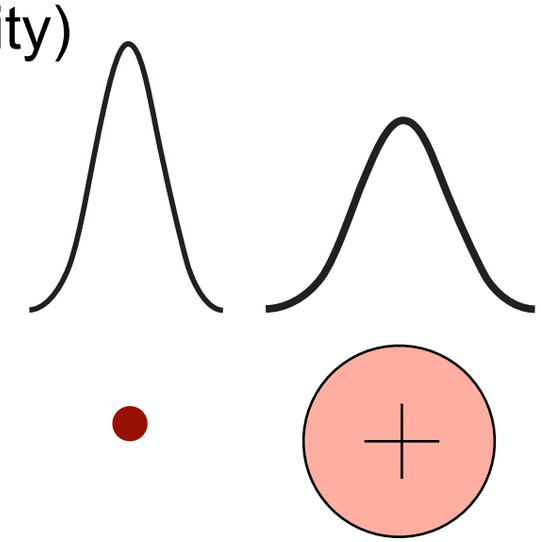
adaptation profile



Problem!

measurement noise
(random noise / reliability)

wrong prediction or model
(systematic bias / accuracy)



when an error is detected,
what is its cause?

Burge, Ernst & Banks, **J. of Vision** 2008

Kalman Filter

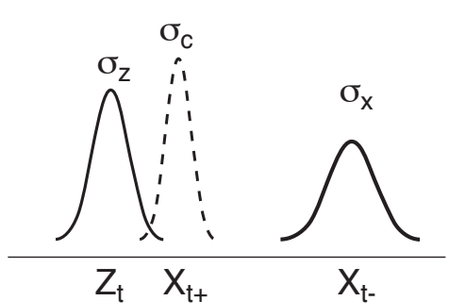
measurement

z_t = measured conflict
σ^2_z = measurement uncertainty

prediction

x_{t-} = expected conflict
σ^2_x = uncertainty of expectation

$$\frac{\sigma_x^2}{\sigma_z^2 + \sigma_x^2} = w_z \qquad w_x = \frac{\sigma_z^2}{\sigma_z^2 + \sigma_x^2}$$



$$\boxed{\begin{aligned}\hat{x}_{t^+} &= w_x \hat{x}_{t^-} + w_z \hat{z}_t \\ &= \hat{x}_{t^-} + K(\hat{z}_t - \hat{x}_{t^-})\end{aligned}}$$

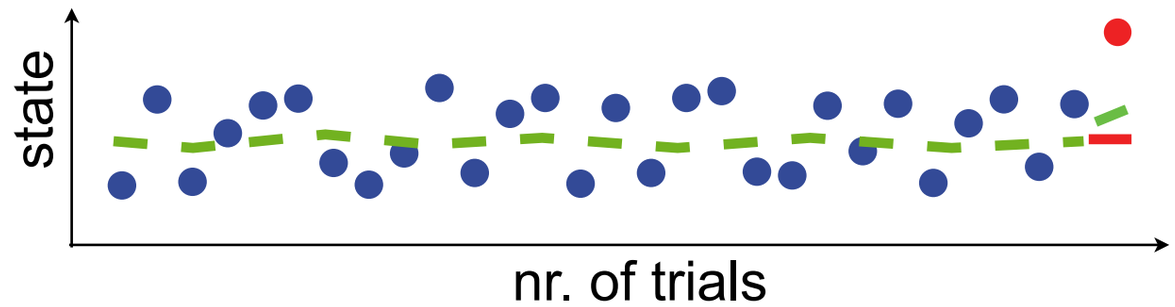
Kalman Gain

$$K = {1/\sigma_z^2} \Big/ (1/\sigma_z^2 + 1/\sigma_x^2)$$

optimal estimate of current bias!

Burge, Ernst & Banks, **J. of Vision** 2008

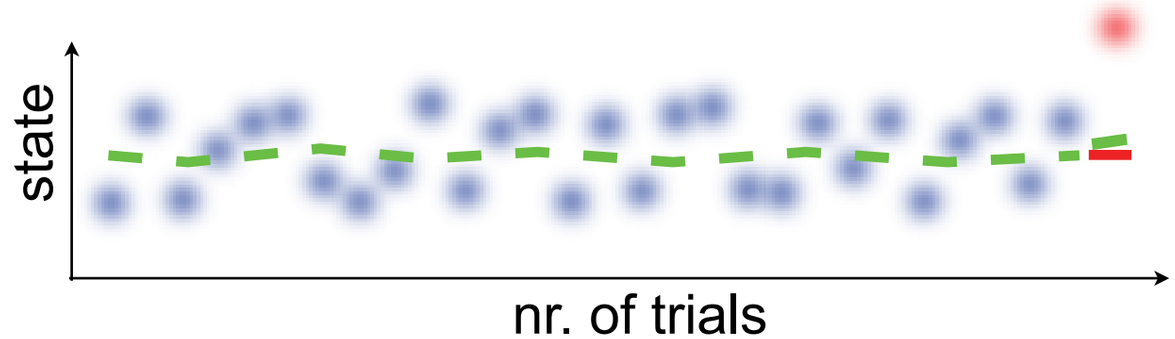
Weighting Example



$\hat{x}_{t^-}$ σ^2_x

$\hat{z}_t$ σ^2_z

$$\hat{x}_{t^+} = w_x \hat{x}_{t^-} + w_z \hat{z}_t$$
$$= \hat{x}_{t^-} + K(\hat{z}_t - \hat{x}_{t^-})$$

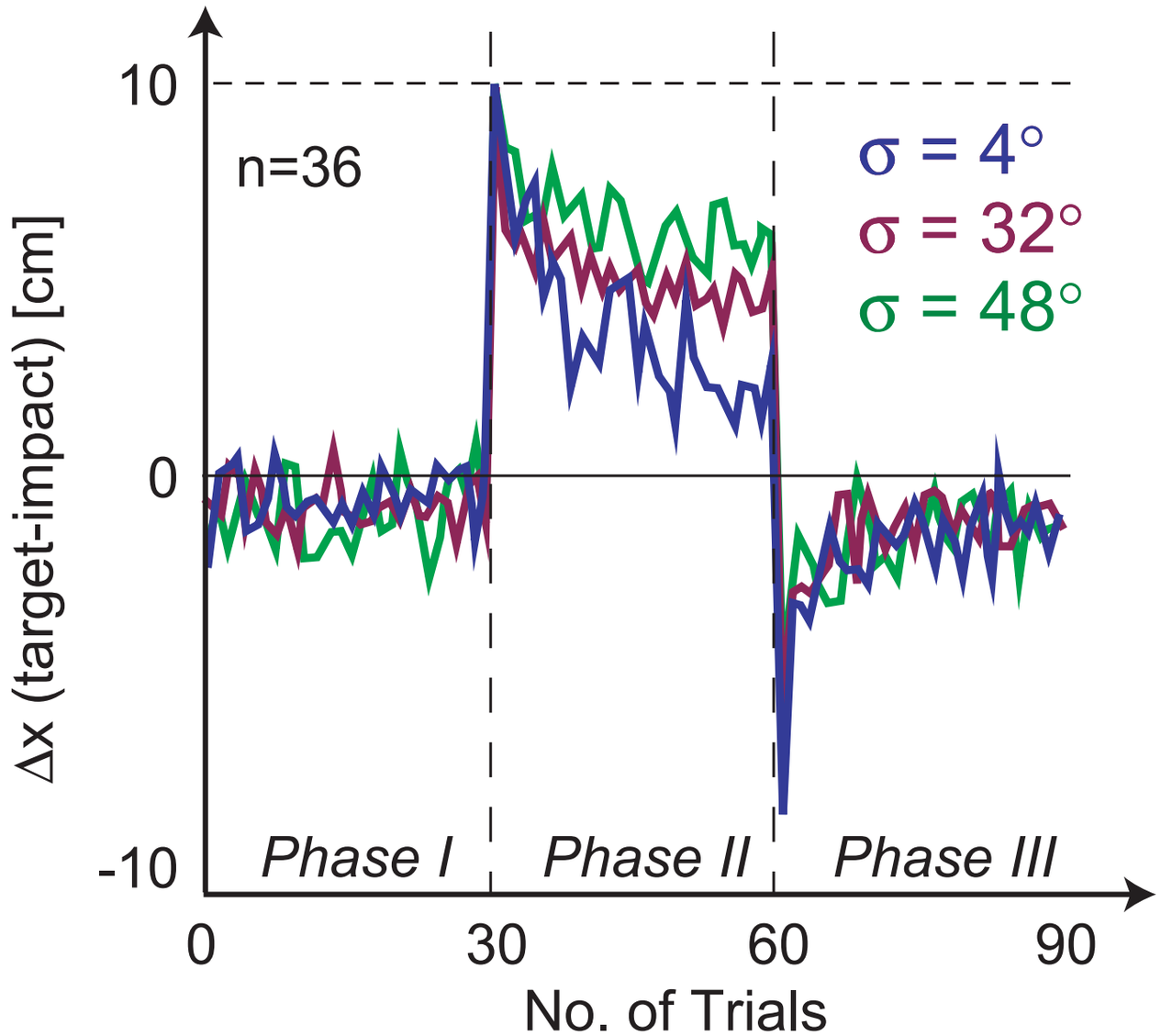


measurement uncertainty (σ^2_z) => large

adaptation => slow

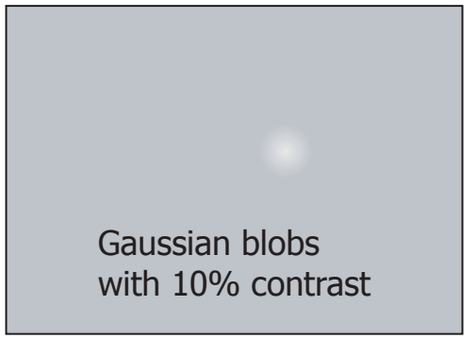
Burge, Ernst & Banks, **J. of Vision** 2008

Adaptation Profile

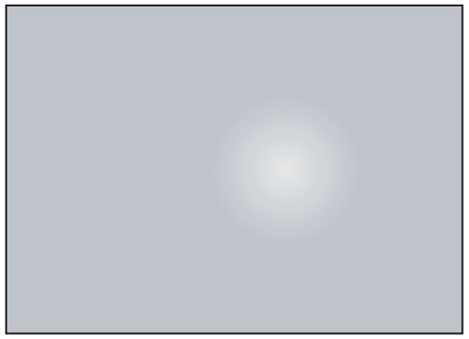


feedback conditions
(three reliability levels)

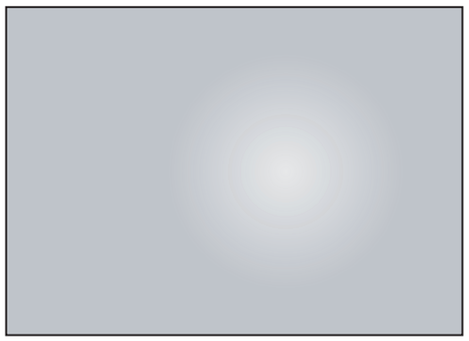
σ = 4°



σ = 32°



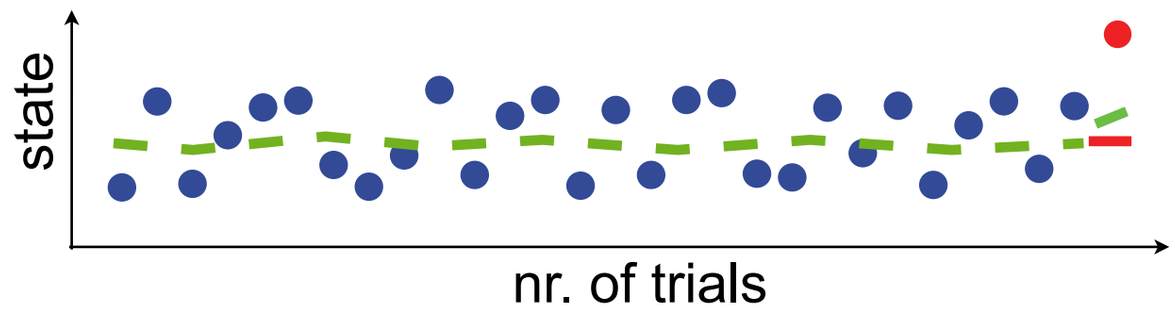
σ = 48°



- Reliability of the feedback signal determines adaptation rate!
- The reliability of the signals has to be known to the perceptual system!

Burge, Ernst & Banks, **J. of Vision** 2008

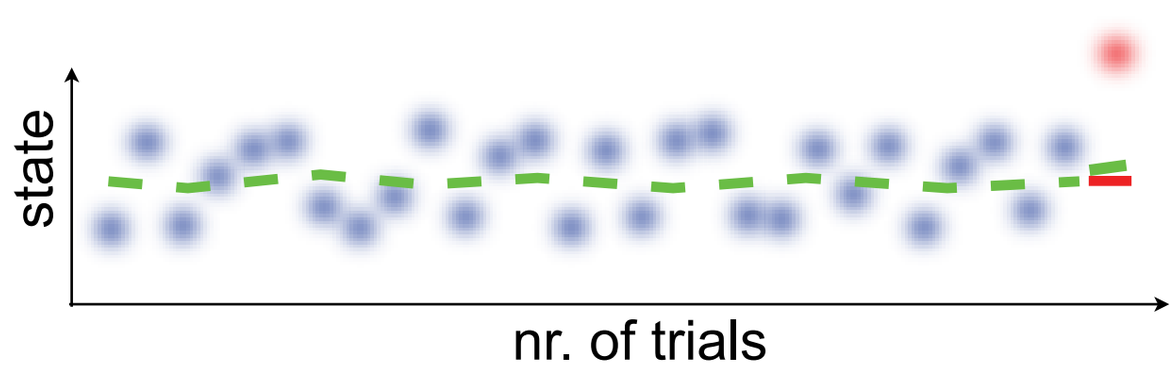
Weighting Example



$\hat{x}_{t^-}$ σ^2_x

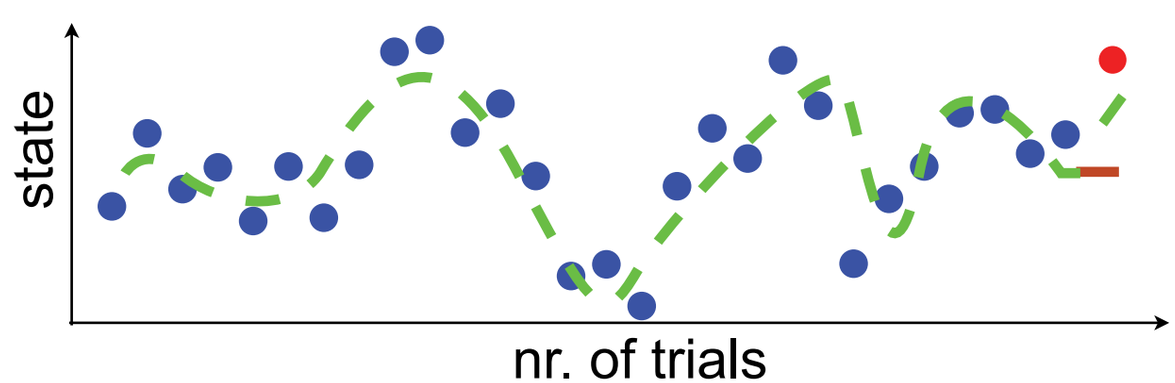
$\hat{z}_t$ σ^2_z

$$\hat{x}_{t^+} = w_x \hat{x}_{t^-} + w_z \hat{z}_t$$
$$= \hat{x}_{t^-} + K(\hat{z}_t - \hat{x}_{t^-})$$



measurement uncertainty (σ^2_z) => large
adaptation => slow

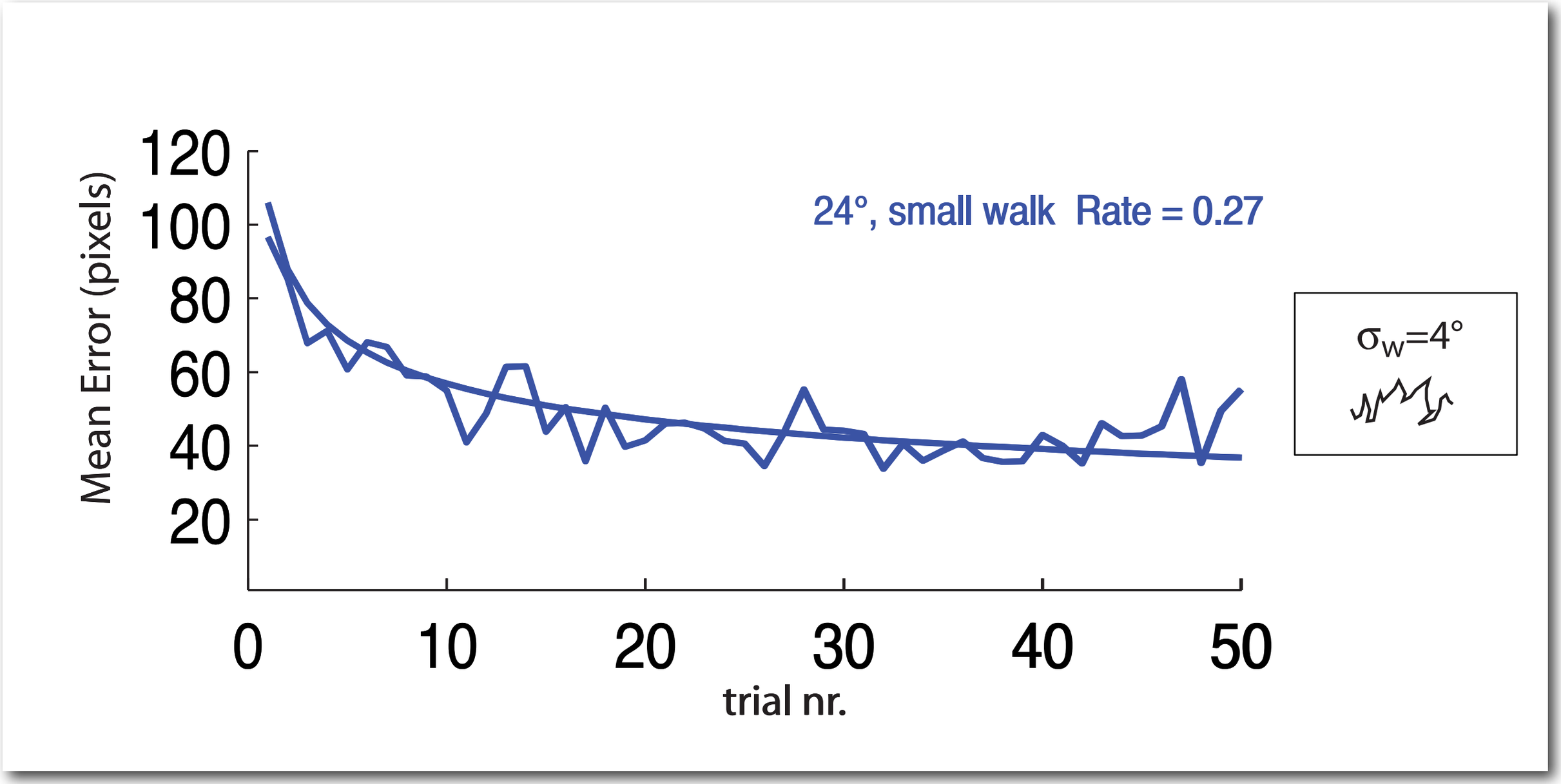
$$K = \frac{1}{1 + \sigma_z^2 / \sigma_x^2}$$



process uncertainty (σ^2_x) => large
adaptation => fast

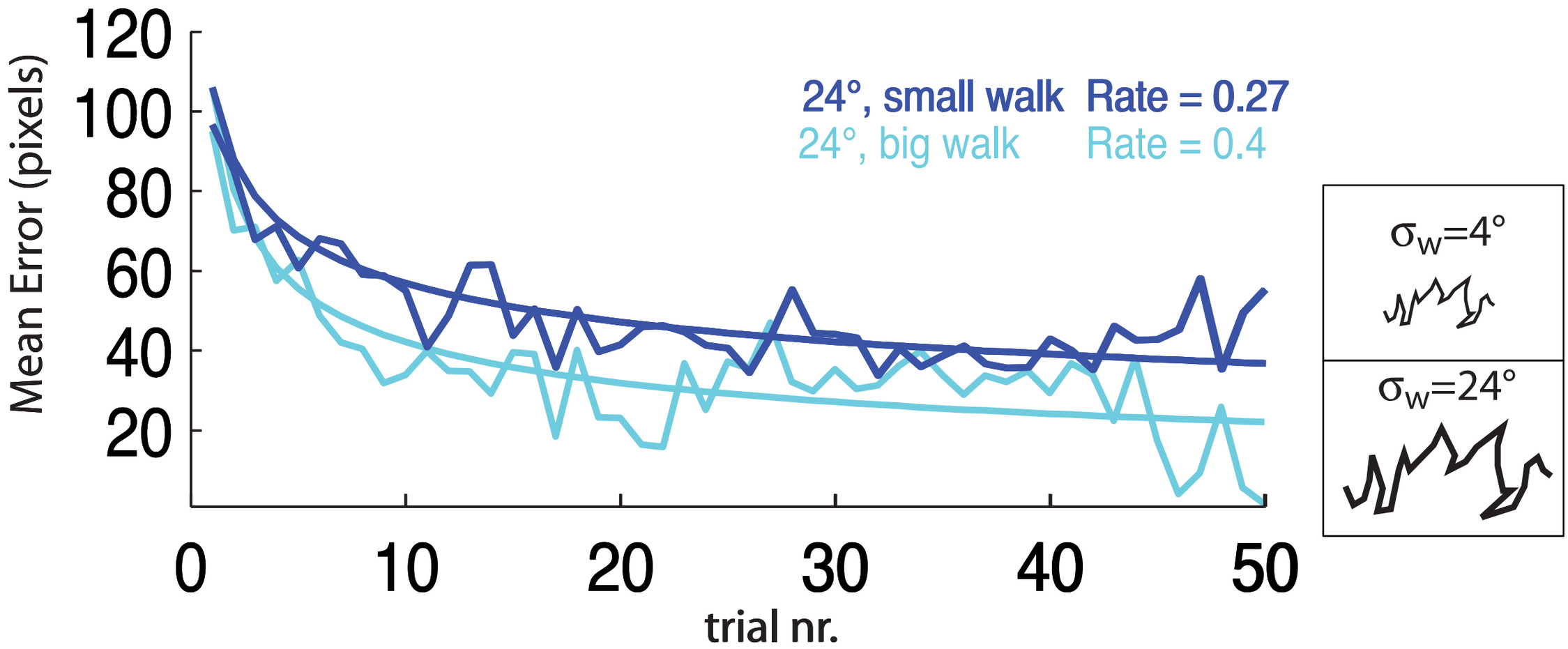
Burge, Ernst & Banks, **J. of Vision** 2008

Stable World



Burge, Ernst & Banks, **J. of Vision** 2008

Unstable World



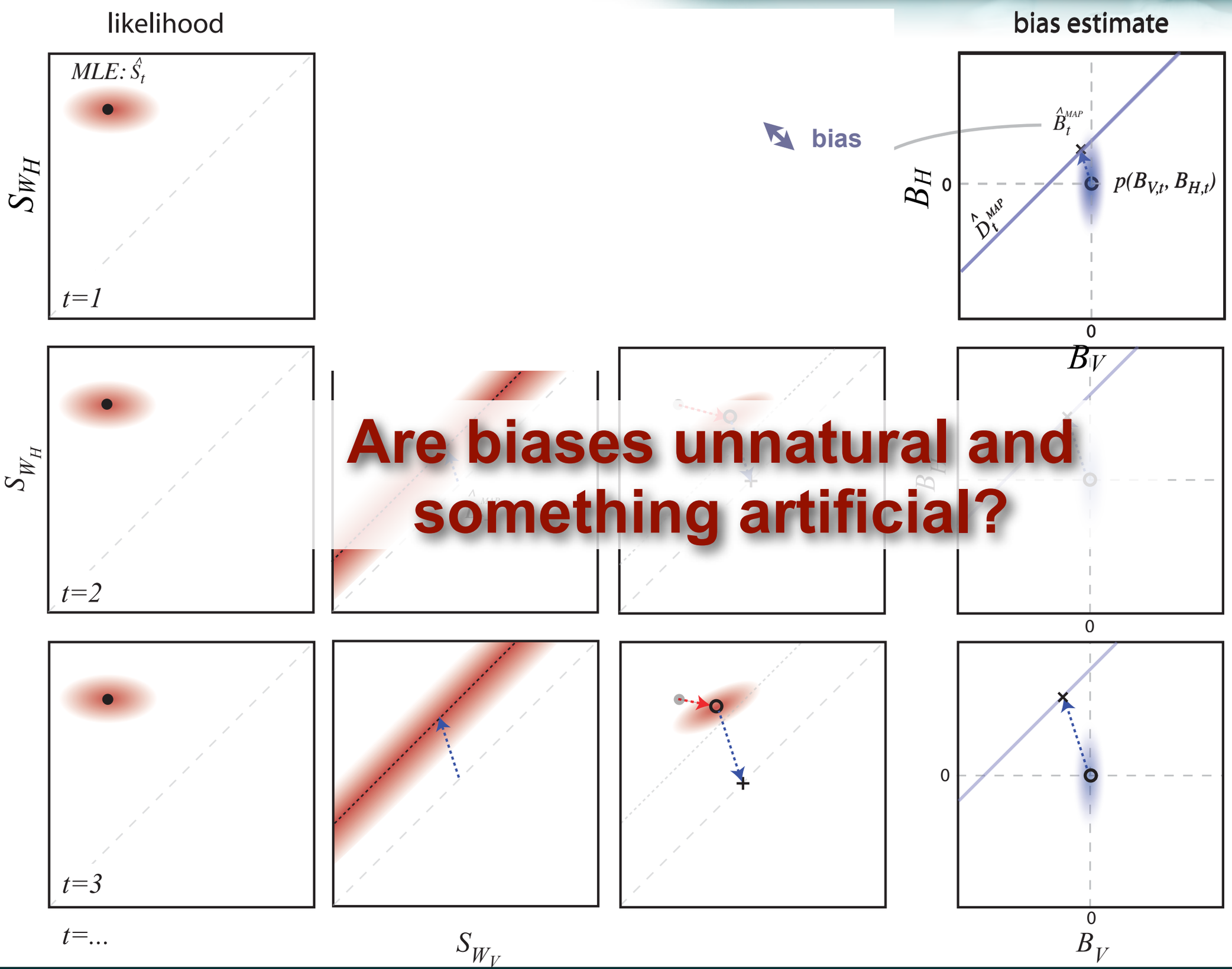
Burge, Ernst & Banks, **J. of Vision** 2008

Summary: Recalibration

- Adaptation rate depends on reliability of visual feedback.
  ➜ unreliable = slow adaptation
- Adaptation rate depends on uncertainty in predicting the wold state.
  ➜ uncertain = fast adaptation
- In first approximation the Kalman-Filter as an „ideal observer“ is a good predictor for human adaptation performance.

Burge, Ernst & Banks, **J. of Vision** 2008

From Integration to Remapping



Are biases unnatural and something artificial?

Di Luca, Machulla & Ernst, **J. of Vision** 2009

Ernst & Di Luca (in press)

“Do people really walk in circles if they lose their way in the desert, and, if so, why?”

WDR.de

Souman, Frissen, Sreenivasa & Ernst, ***Current Biology*** (2009)

Common belief

John Tolkien, The Two Towers

Mark Twain, Roughing it

Leo Tolstoy, Master and Man

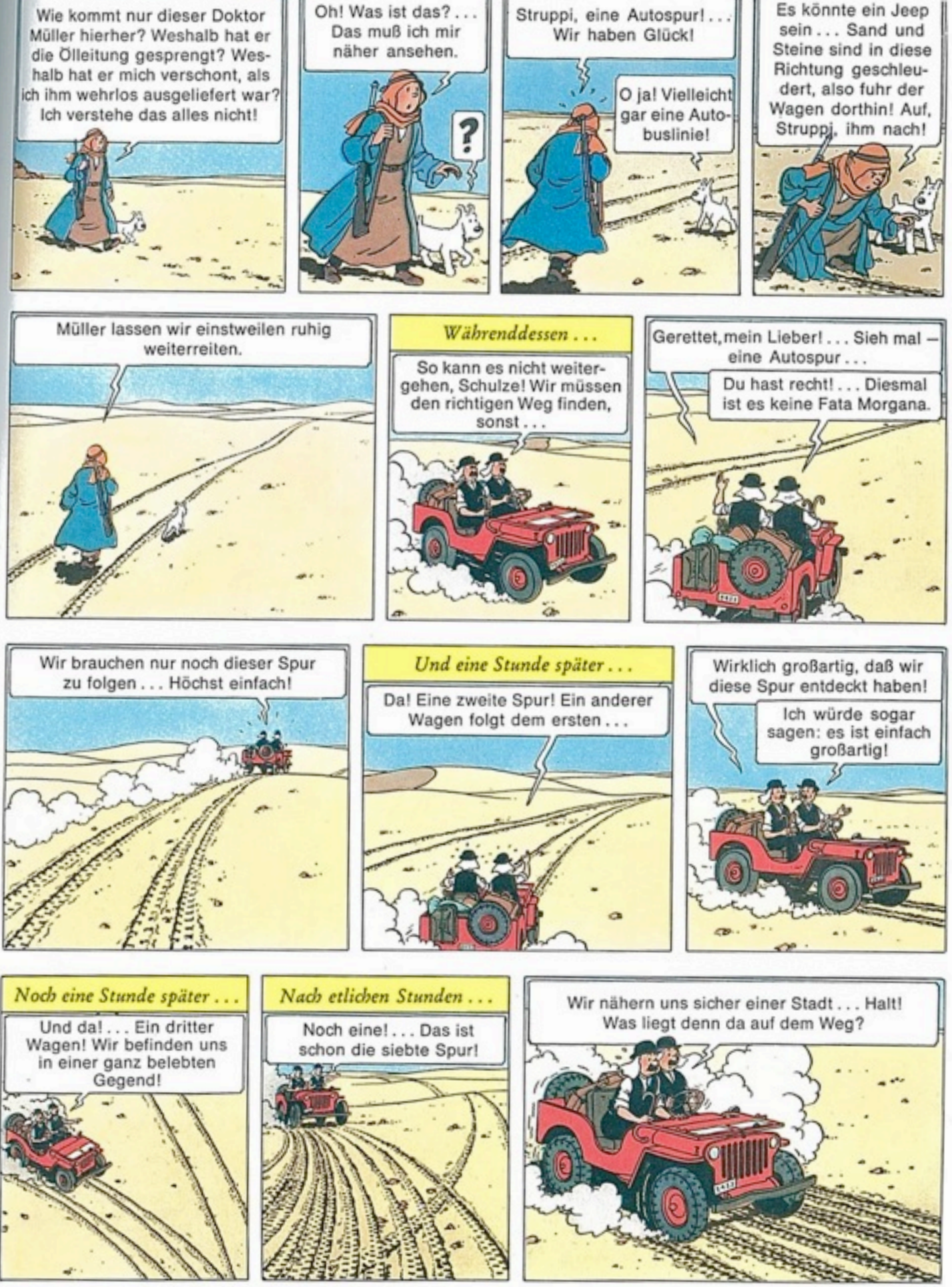
Common belief

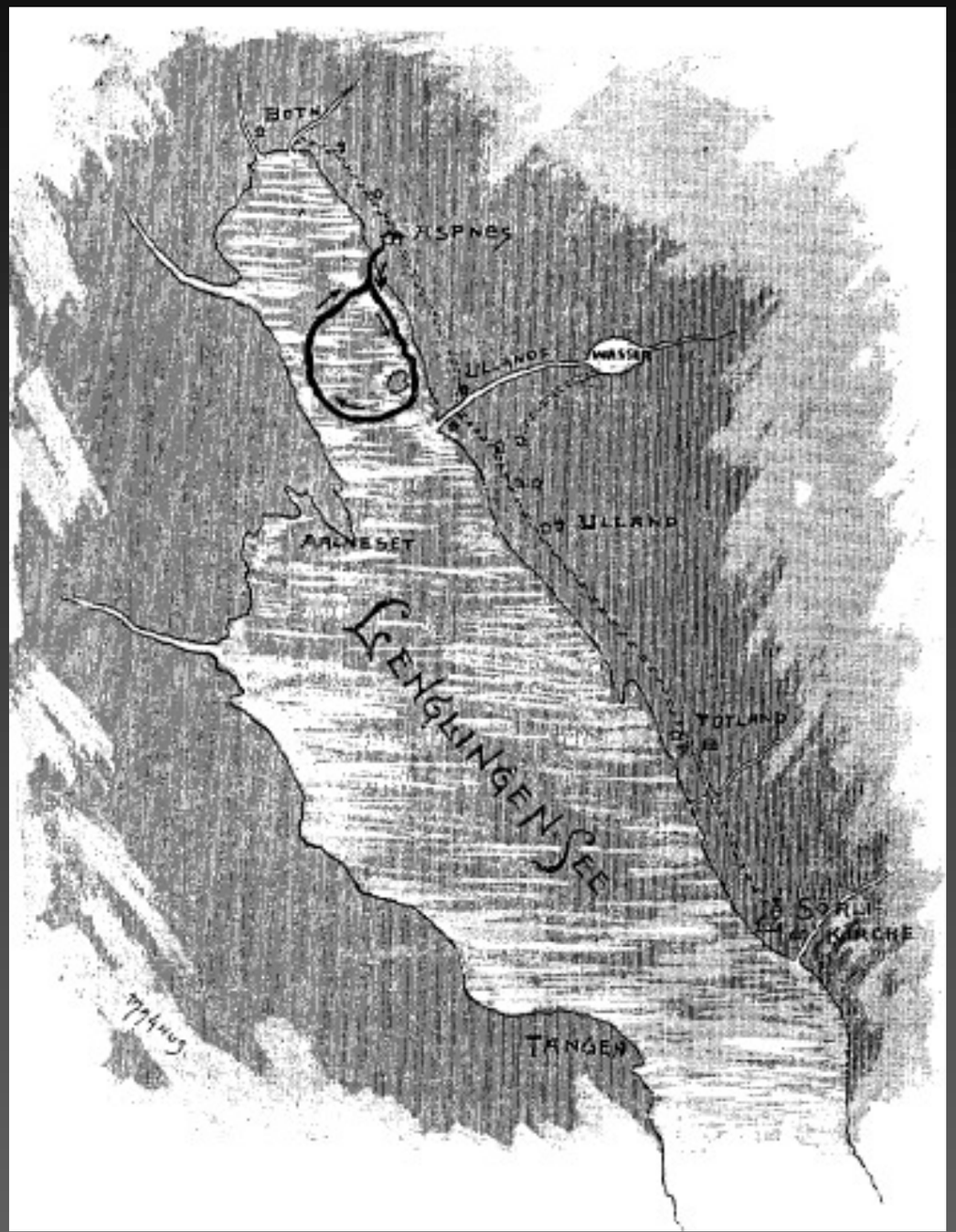
The Flight of the Phoenix

Laurel & Hardy, Beau Hunks

Blair Witch Project

Anecdotes





Guldberg (1897)

Sahara (Tunesia)

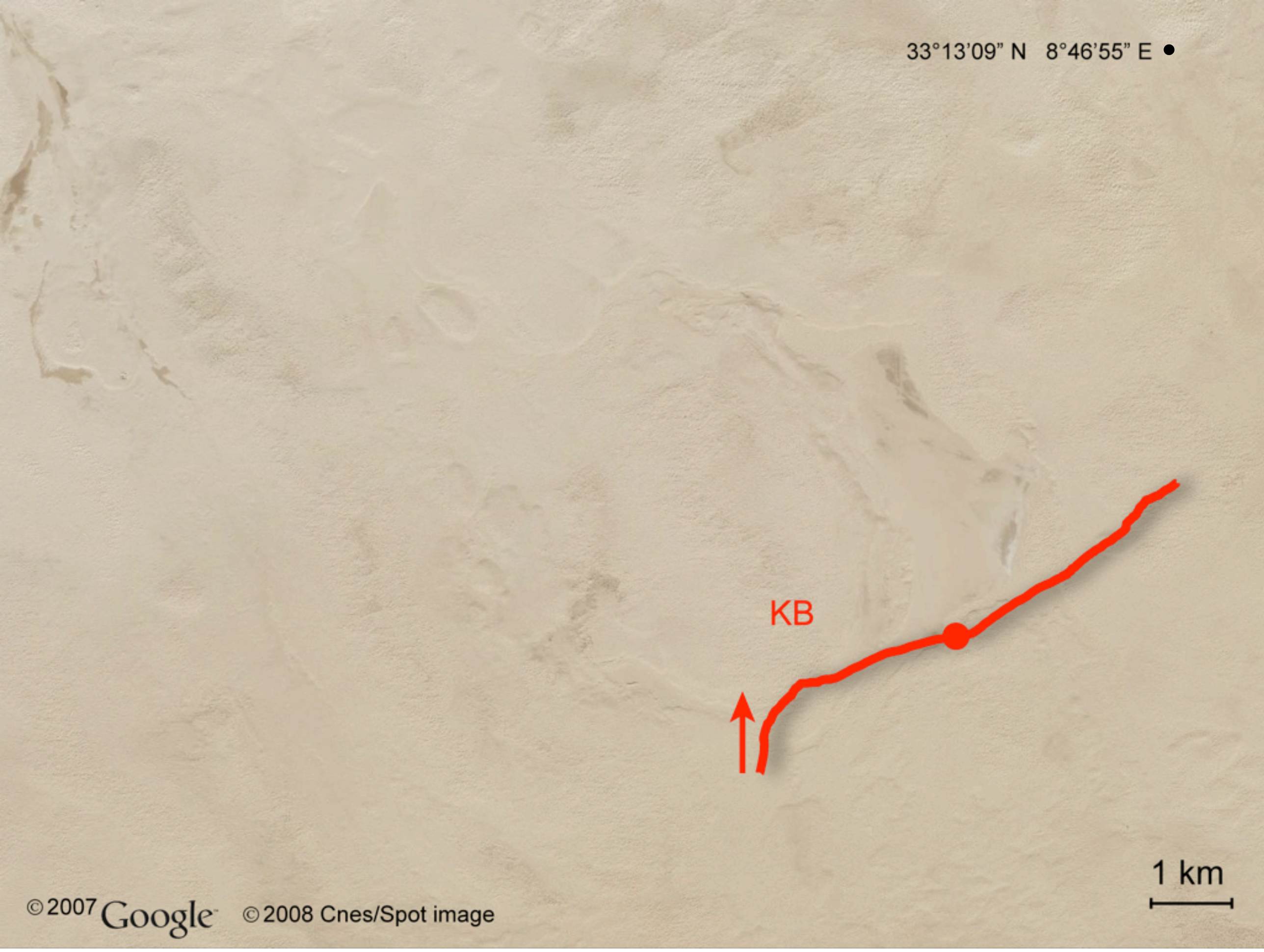
Desert Walks

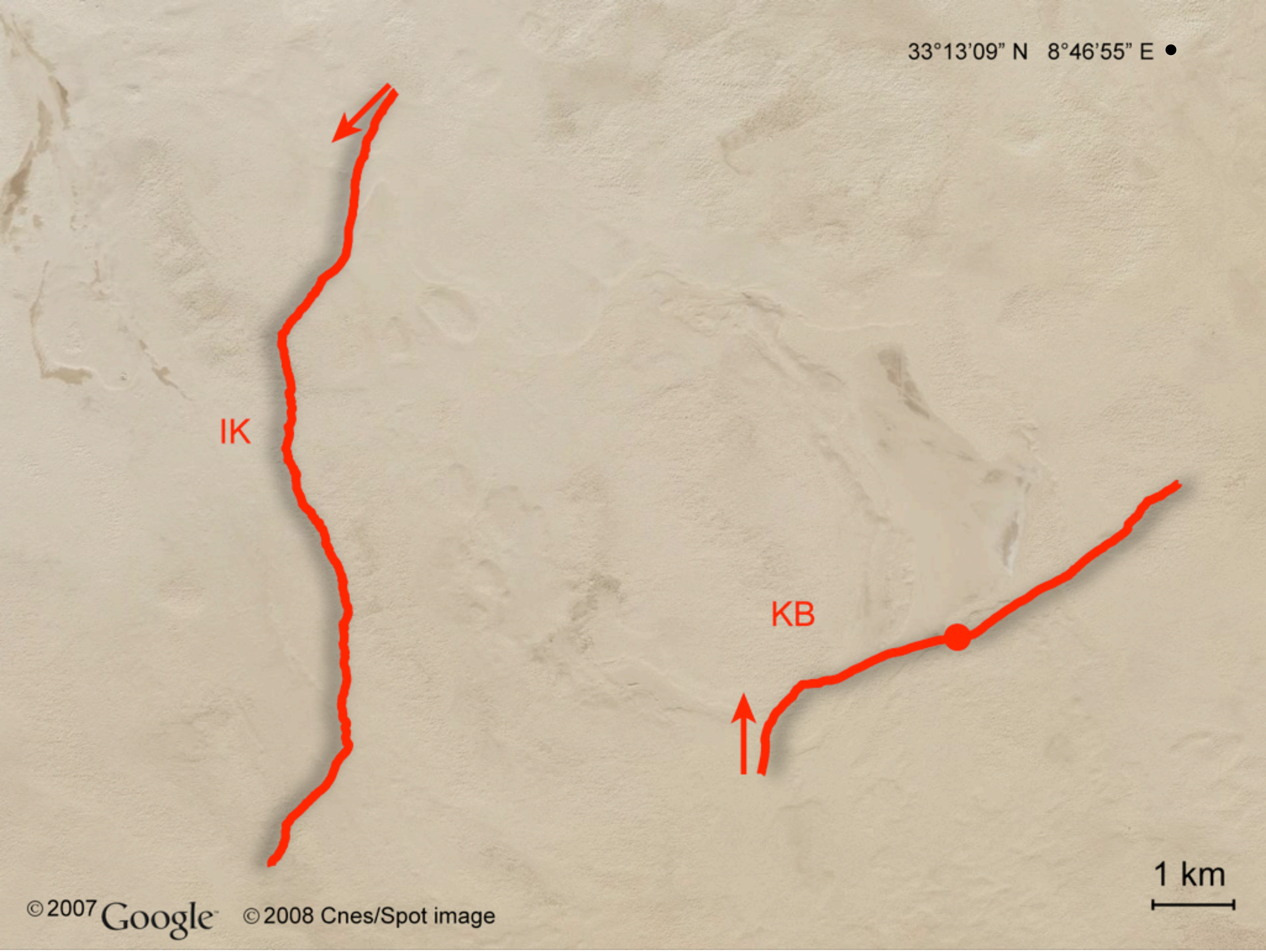
Task:
keep walking in the direction indicated at the beginning of the walk

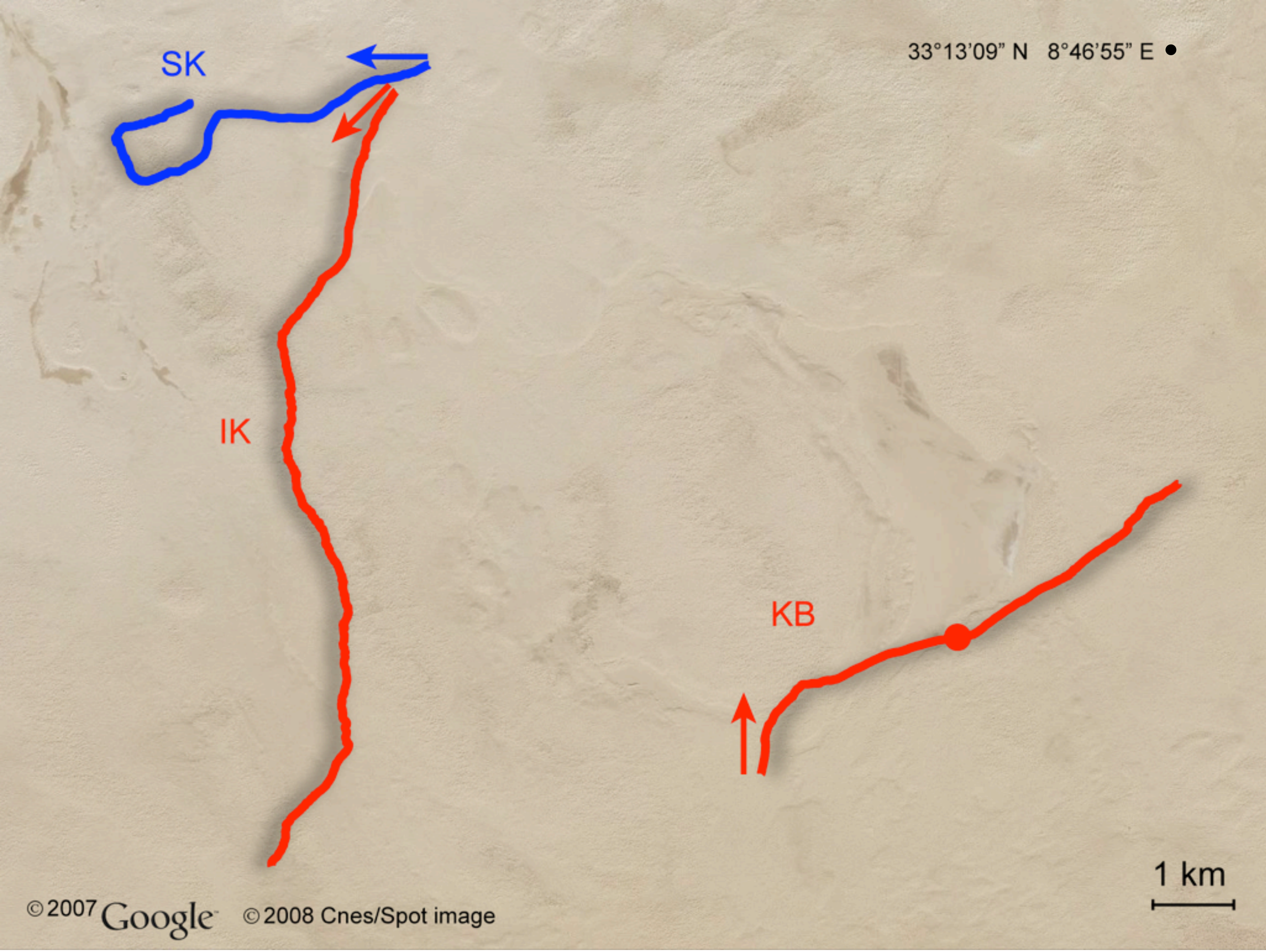
Condition:
- ~3.5 hours
- 45°C
- no navigational instruments

Measurements:
GPS data (1Hz; accuracy ~3m)

Jan Souman, Ilja Frissen, Manish Sreenivasa, Marc Ernst, *Current Biology* (2009)


33°13'09" N 8°46'55" E
KB
1 km
©2007 Google
©2008 Cnes/Spot image


33°13'09" N 8°46'55" E
IK
KB
1 km
©2007 Google
©2008 Cnes/Spot image


SK
33°13'09" N 8°46'55" E
IK
KB
1 km
©2007 Google
©2008 Cnes/Spot image


Google
Bienwald (Germany)
Tübingen

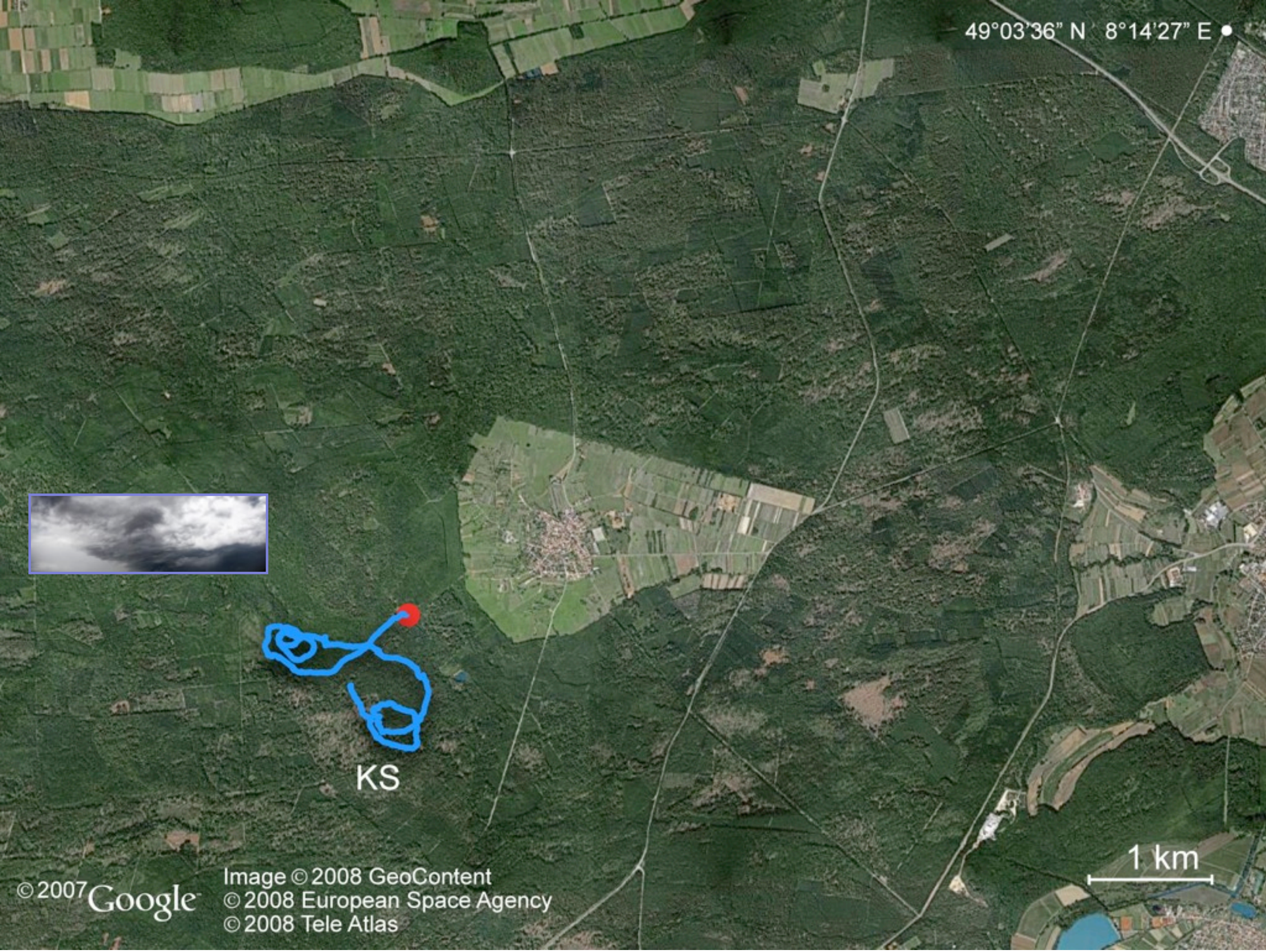
Forrest Walks

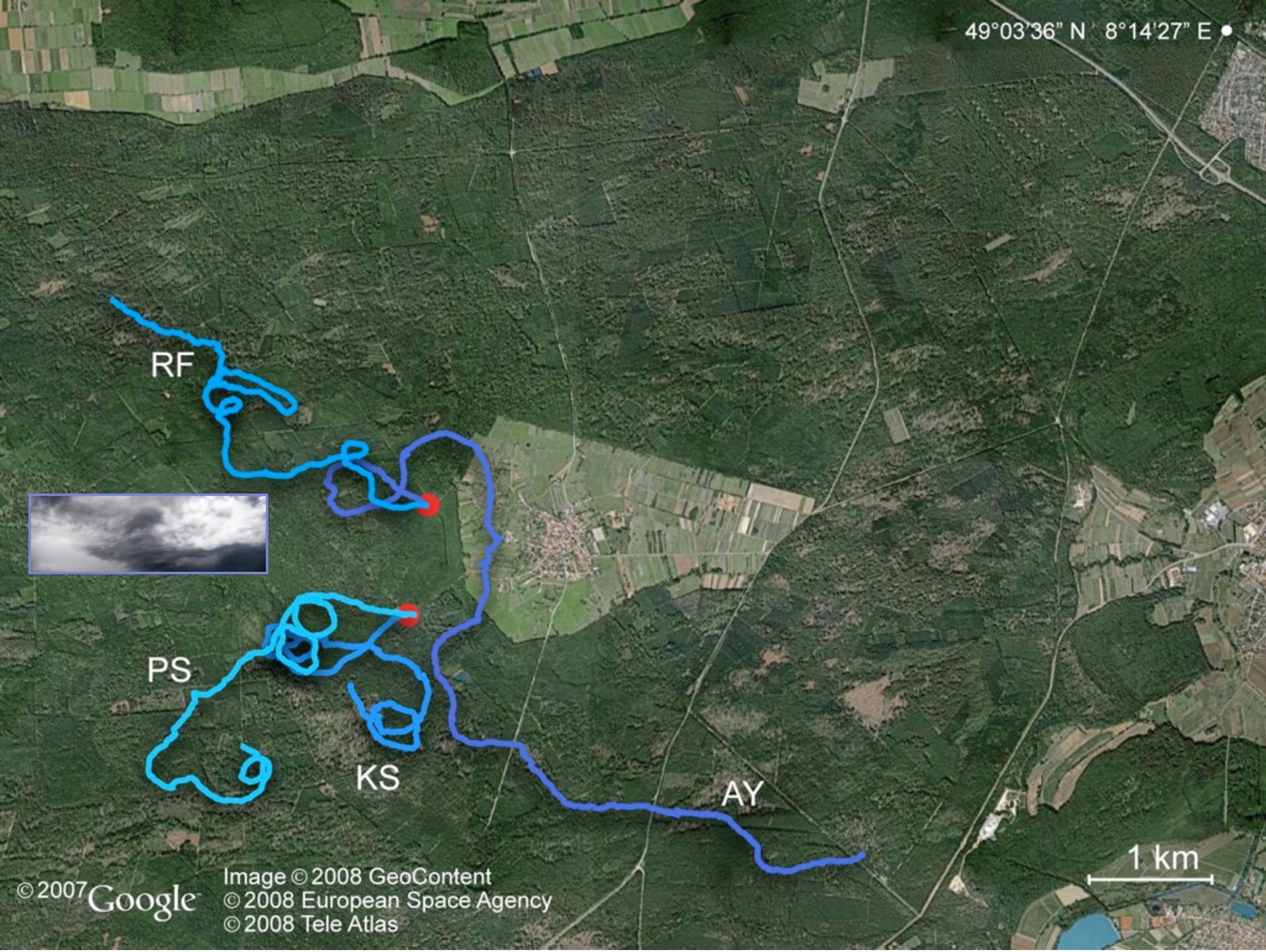
Task:
keep walking in the direction indicated at the beginning of the walk

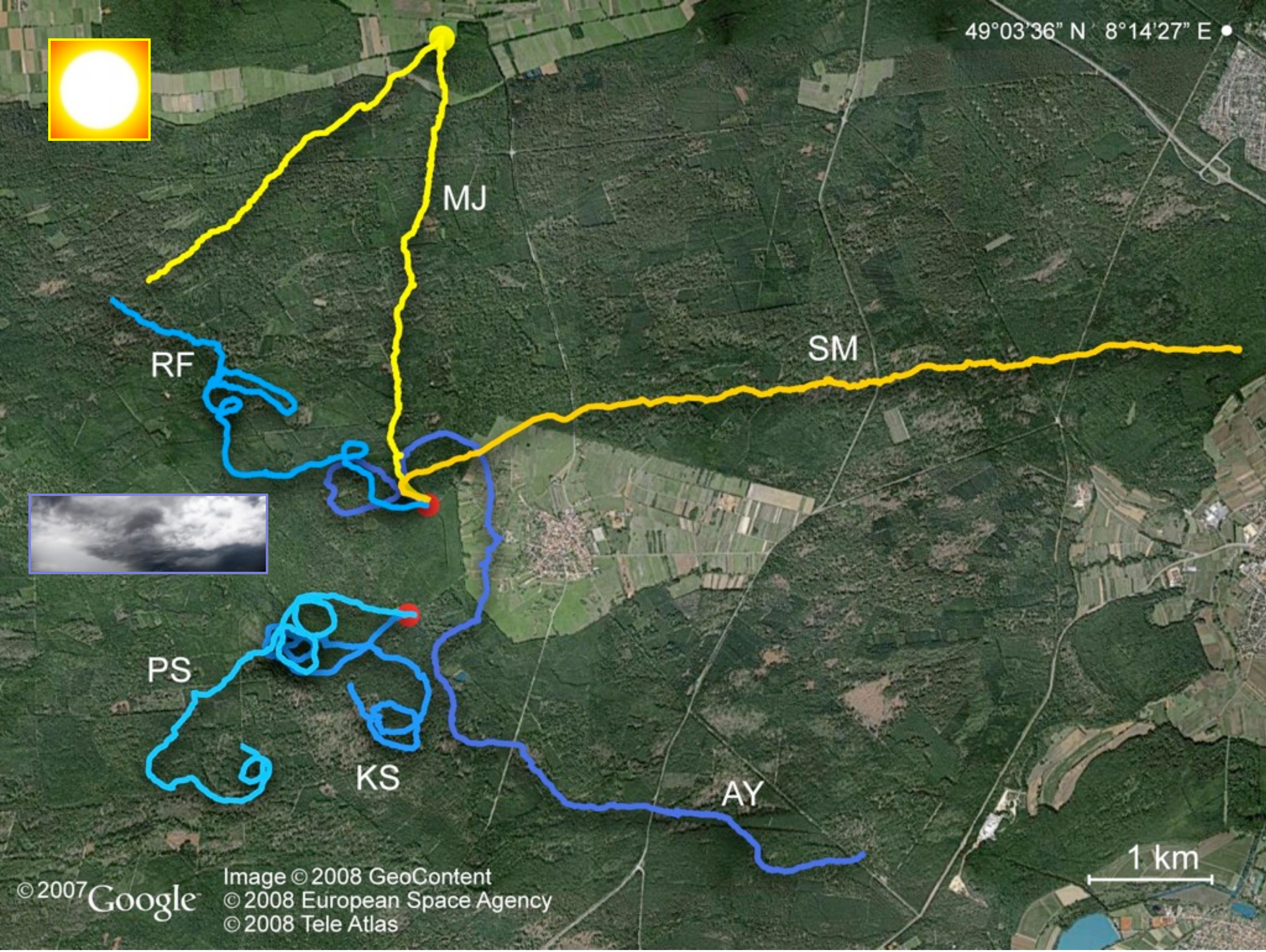
Conditions:
- sunny / cloudy
- 4 hours
- no navigational instruments

Measurements:
GPS data (1Hz; accuracy ~3m)

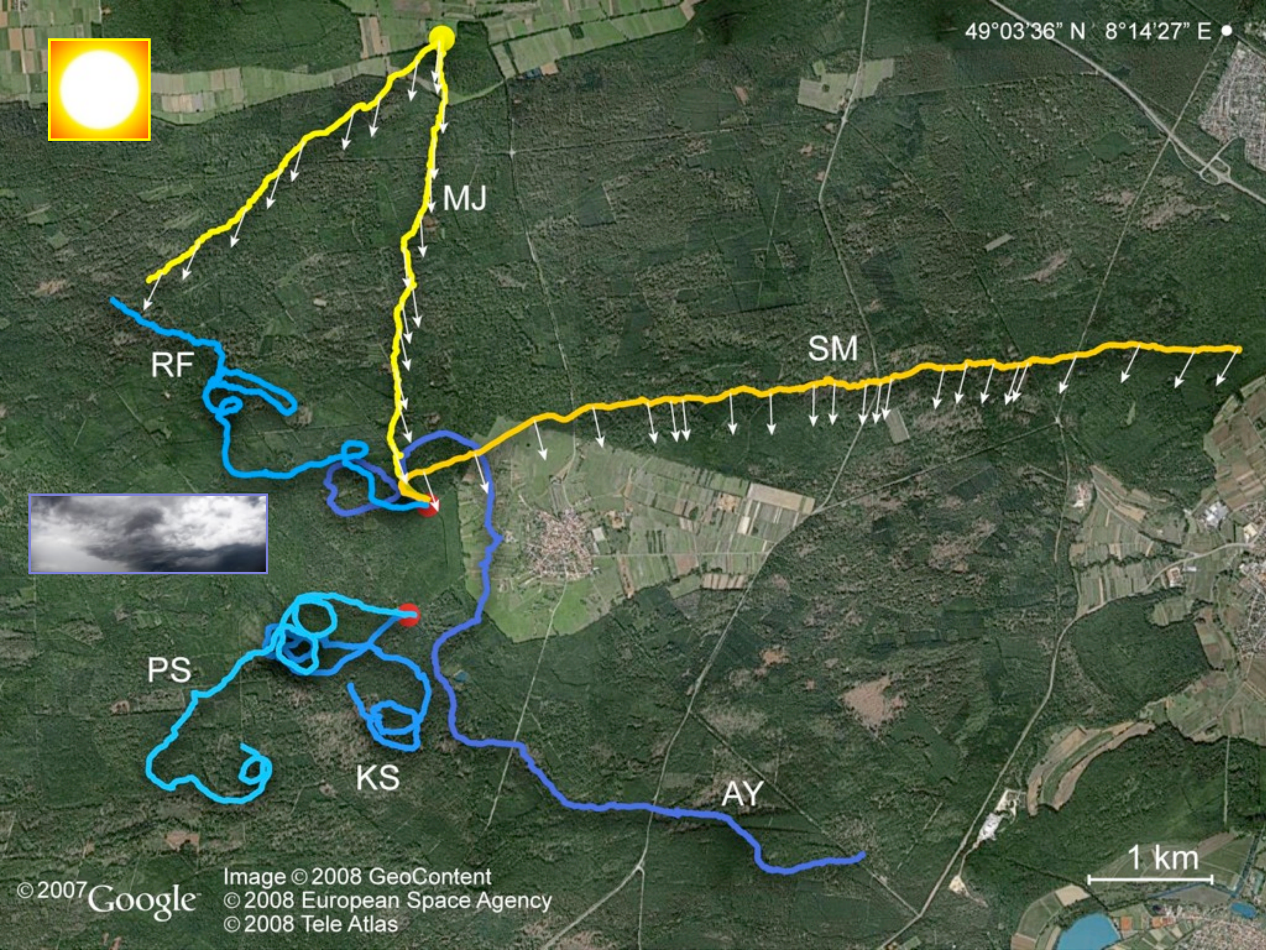
Jan Souman, Ilja Frissen, Manish Sreenivasa, Marc Ernst, *Current Biology* (2009)


49°03'36" N 8°14'27" E
KS
1 km
© 2007 Google
Image © 2008 GeoContent
© 2008 European Space Agency
© 2008 Tele Atlas

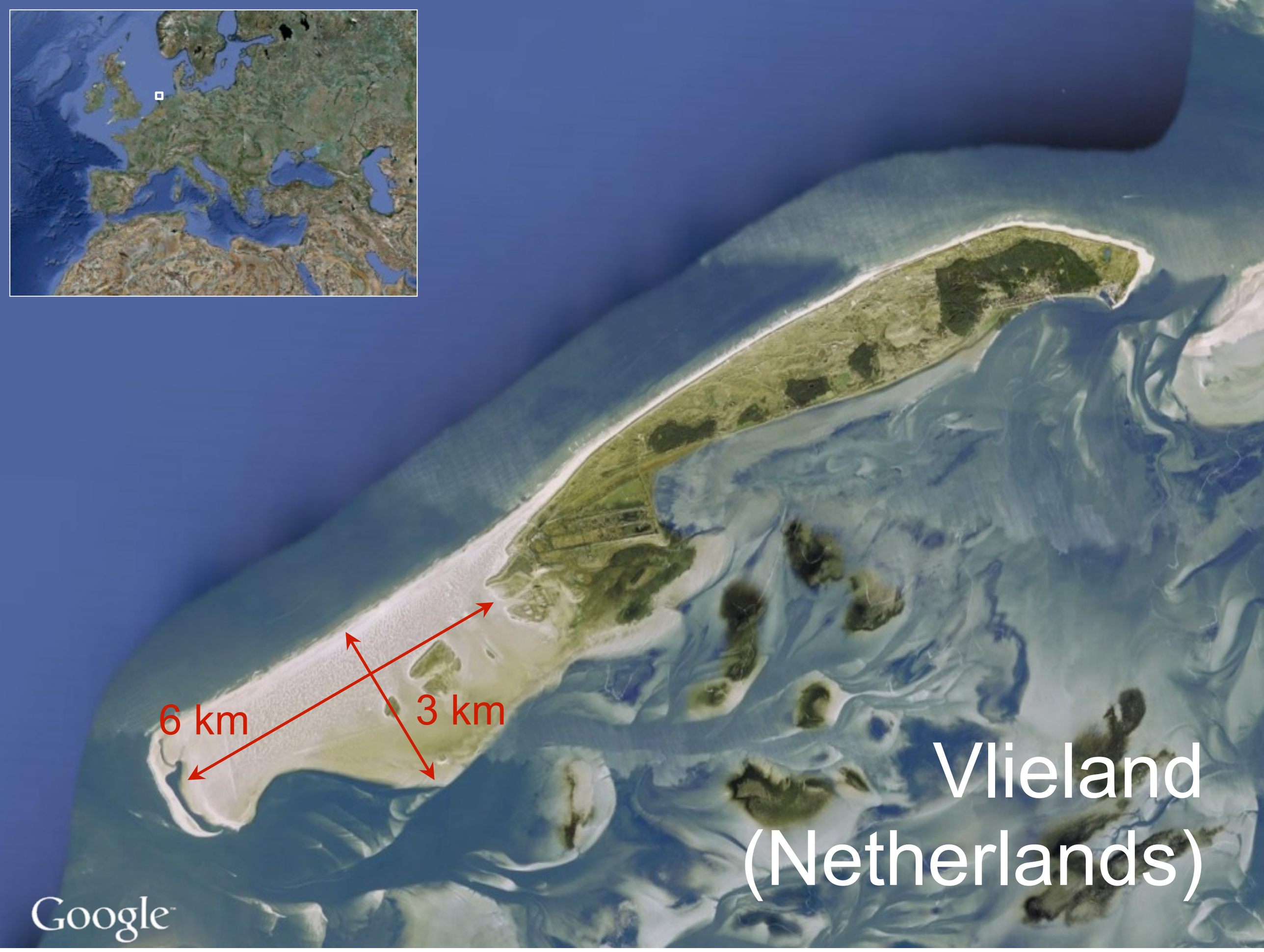

49°03'36" N 8°14'27" E
RF
PS
KS
AY
1 km
©2007 Google
Image © 2008 GeoContent
© 2008 European Space Agency
© 2008 Tele Atlas



Mittwoch, 10. November 2010



Mittwoch, 10. November 2010

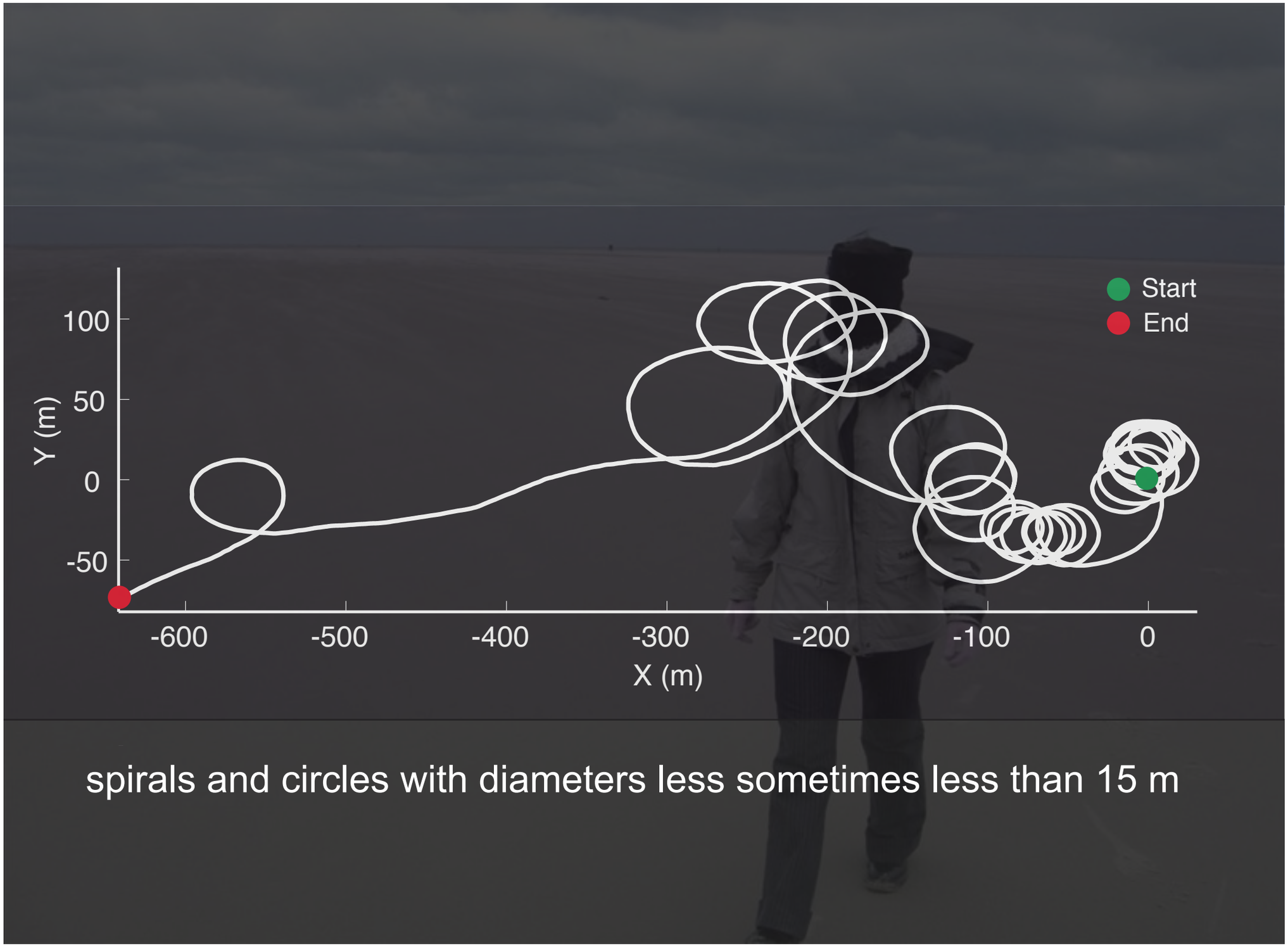

6 km
3 km
Vlieland
(Netherlands)
Google


MILITAIR
OEFENTERREIN
LEVENSGEVAARLIJK
DIT TERREIN IS GEVAARLIJK WANNEER OP DIT BORD
OF OP DE TOREN EEN RODE VLAG IS GEPLAATST
PAS OP
ONONTPLOFTE AMMUNITIE
HET RAPEN VAN HULZEN EN PROJECTIELEN
IS GEVAARLIJK EN VERBODEN
PERSONEN WELKE WORDEN AANGETROFFE
IN HET BEZIT VAN AMMUNITIE ZULLEN
STRAFRECHTELIJK WORDEN VERVOL
WARNUNG
SIE BETRETEN EIN SCHIESZGEBIET FÜR FLUGZEUGEN
WENN GESCHOSSEN WIRD IST DAS GEBIET
MARKIERT MIT ROTEN FAHNEN
BETRETEN IST LEBENSGEFÄHRLICH UND VERBOTEN
WARNING
YOU ARE APPROACHING AN AIRCRAFT GUNNERY RANGE
WHEN IN USE THE DANGER AREA IS MARKED
WITH RED FLAGS
ENTRANCE IS THEN VERY DANGEROUS AND FORBIDDEN

Walking blindfolded ...

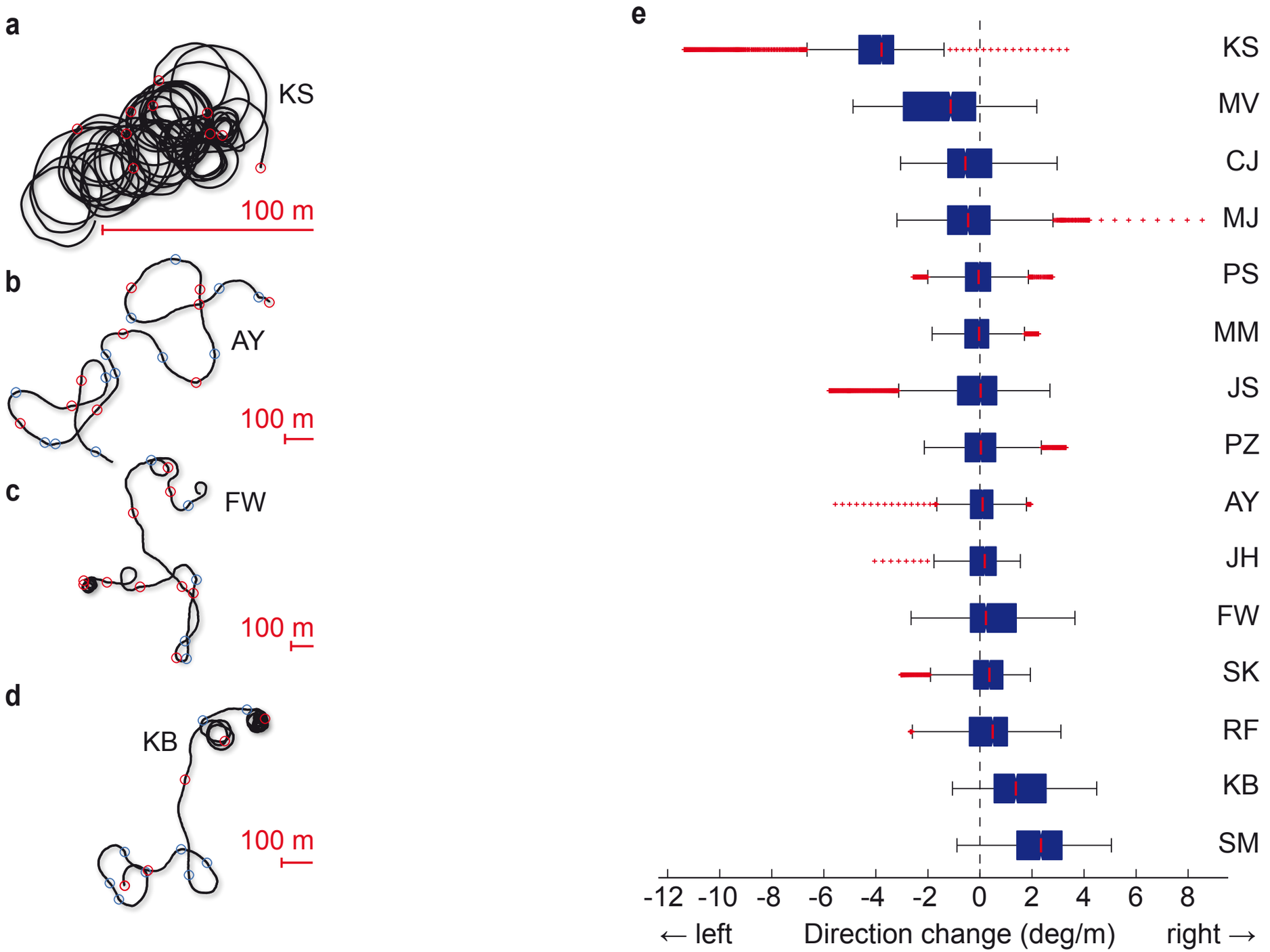
.... as straight as possible!!!

Walk blindfolded ...



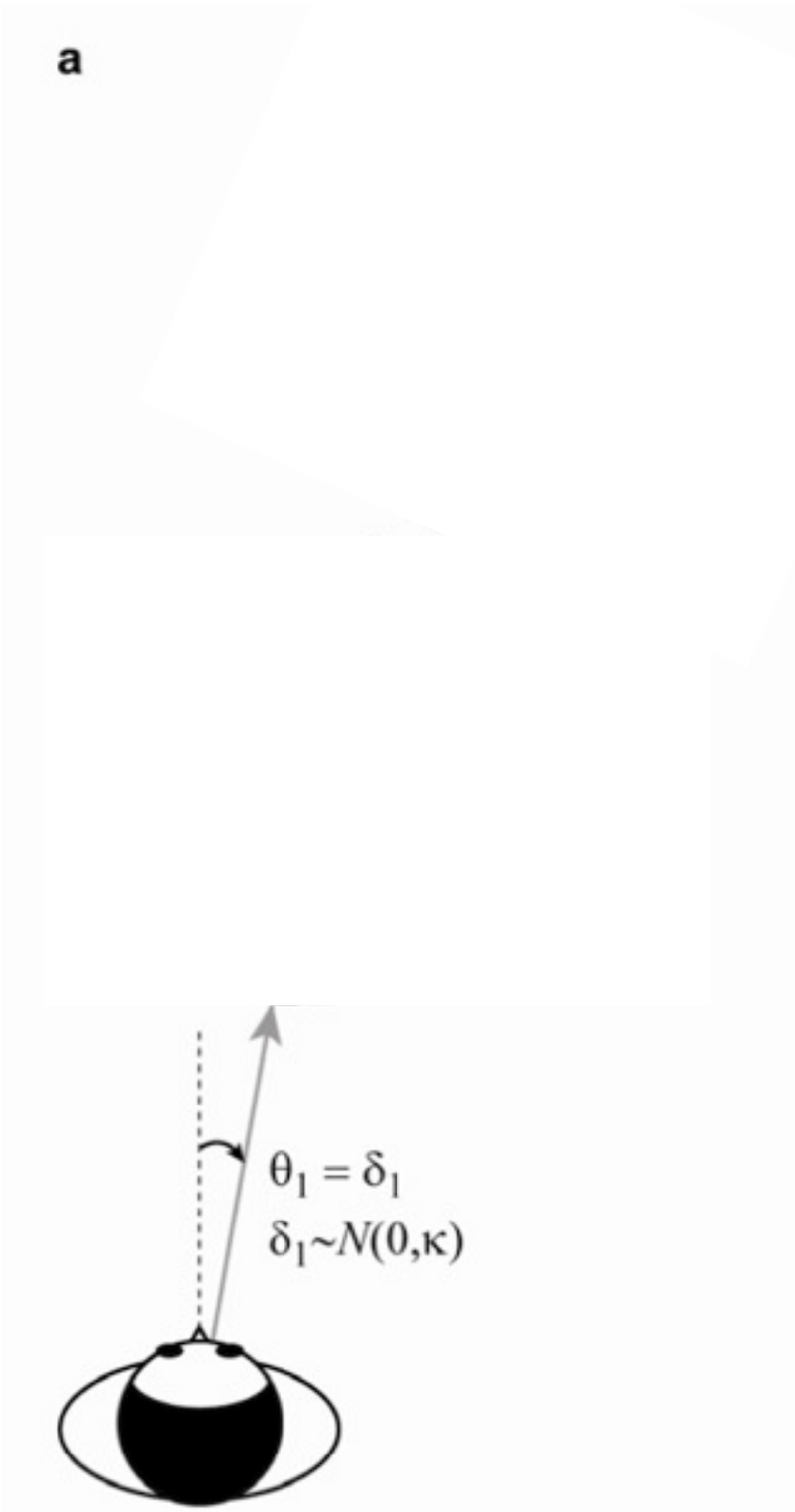
Souman, Frissen, Sreenivasa & Ernst, ***Current Biology*** (2009)

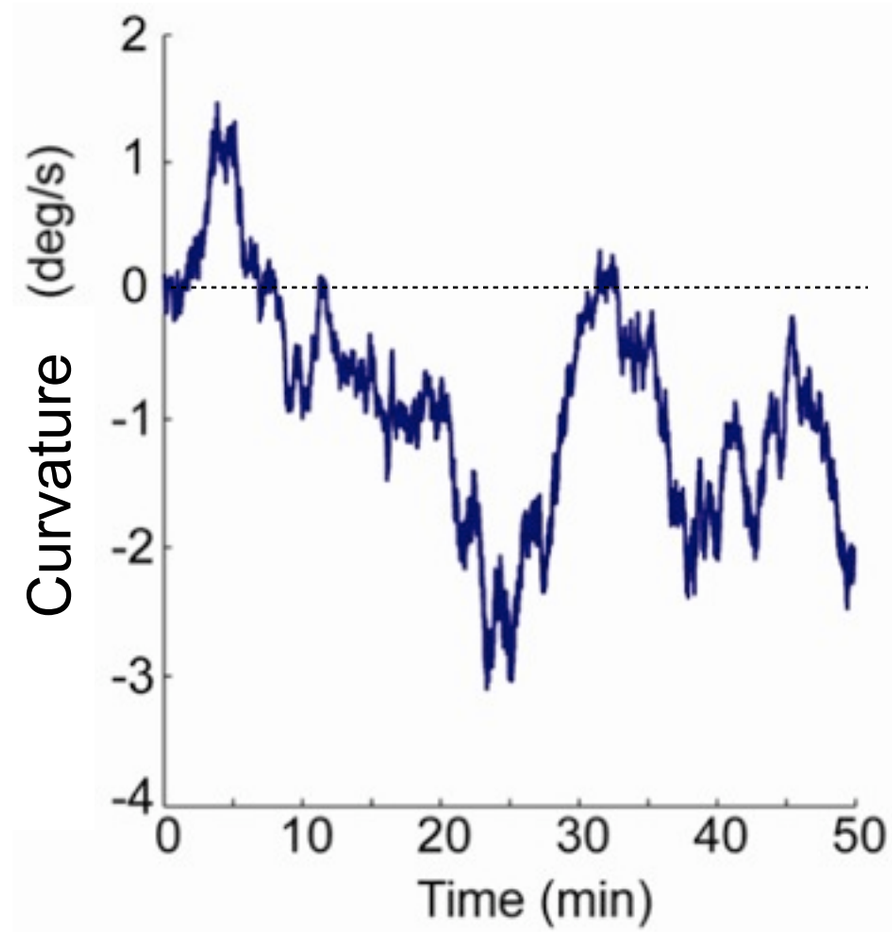
Walking blindfolded ...



Souman, Frissen, Sreenivasa & Ernst, ***Current Biology*** (2009)

Accumulation of Noise

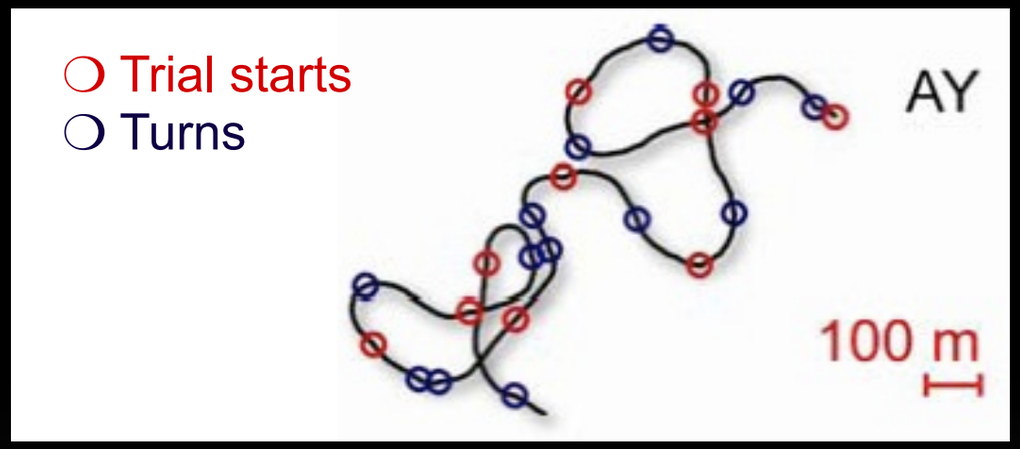


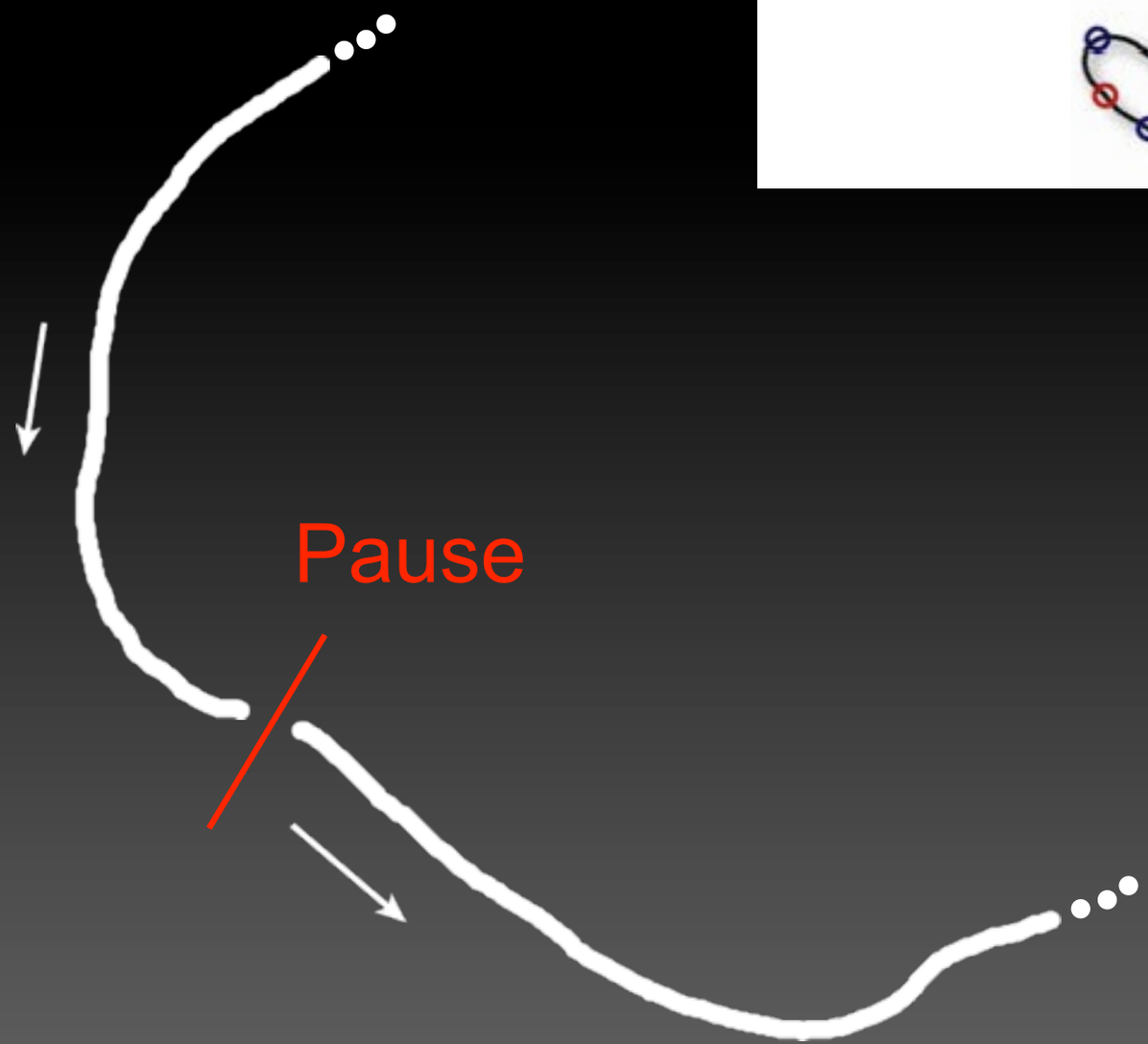


- **The vestibular system accumulates noise when integrating acceleration into a direction estimate**

Souman, Frissen, Sreenivasa & Ernst, ***Current Biology*** (2009)

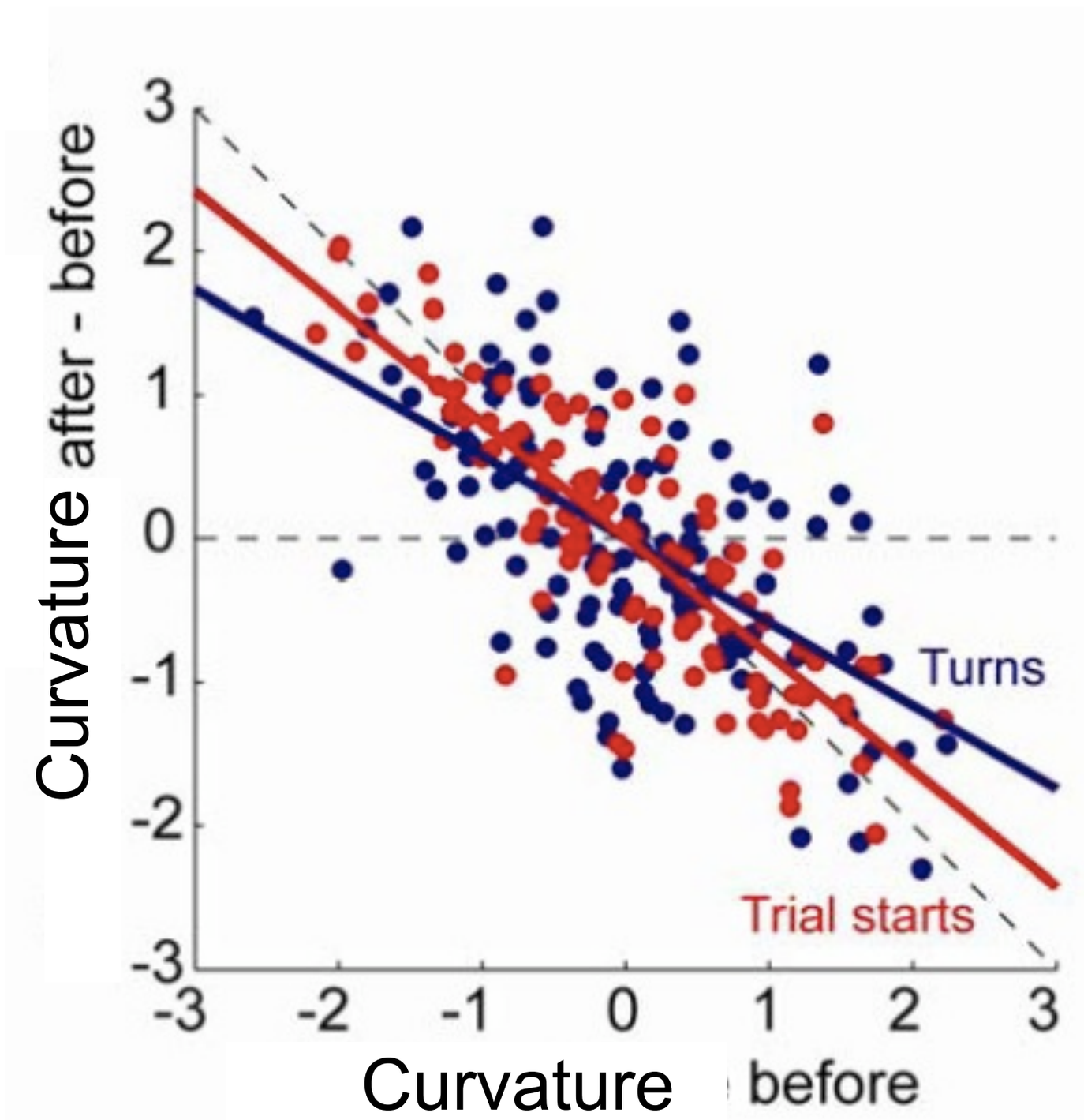
Recalibration





Souman, Frissen, Sreenivasa & Ernst, ***Current Biology*** (2009)

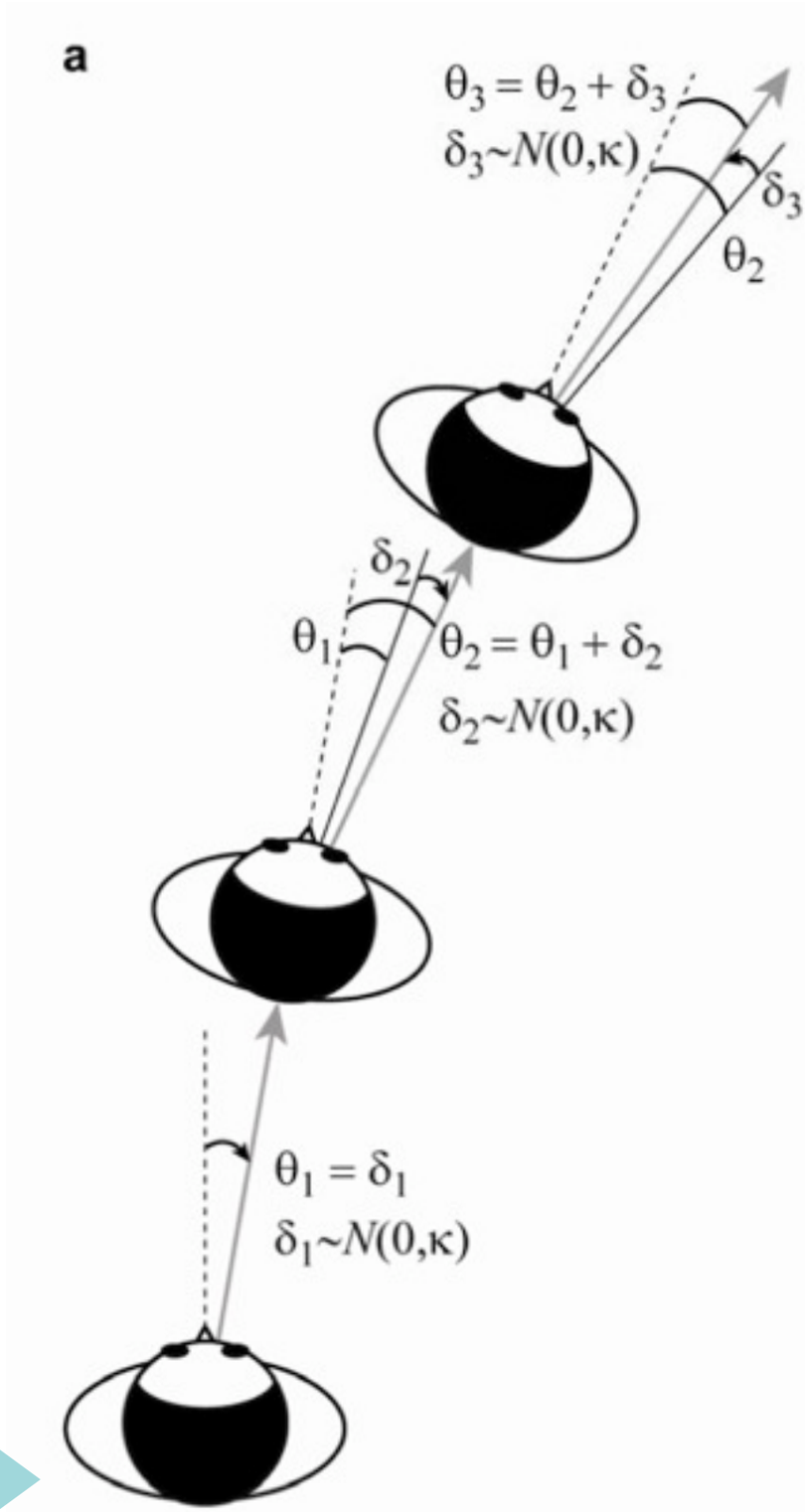
Recalibration

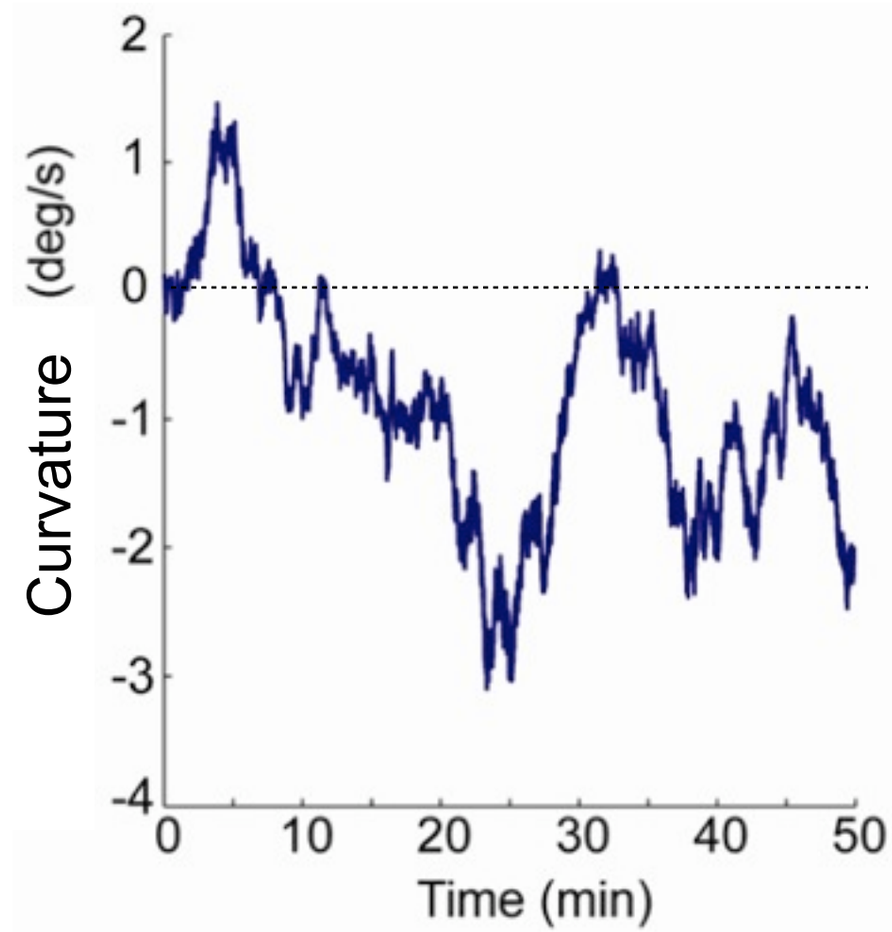


the higher the curvature before the break the more it is corrected after the break
-> recalibration

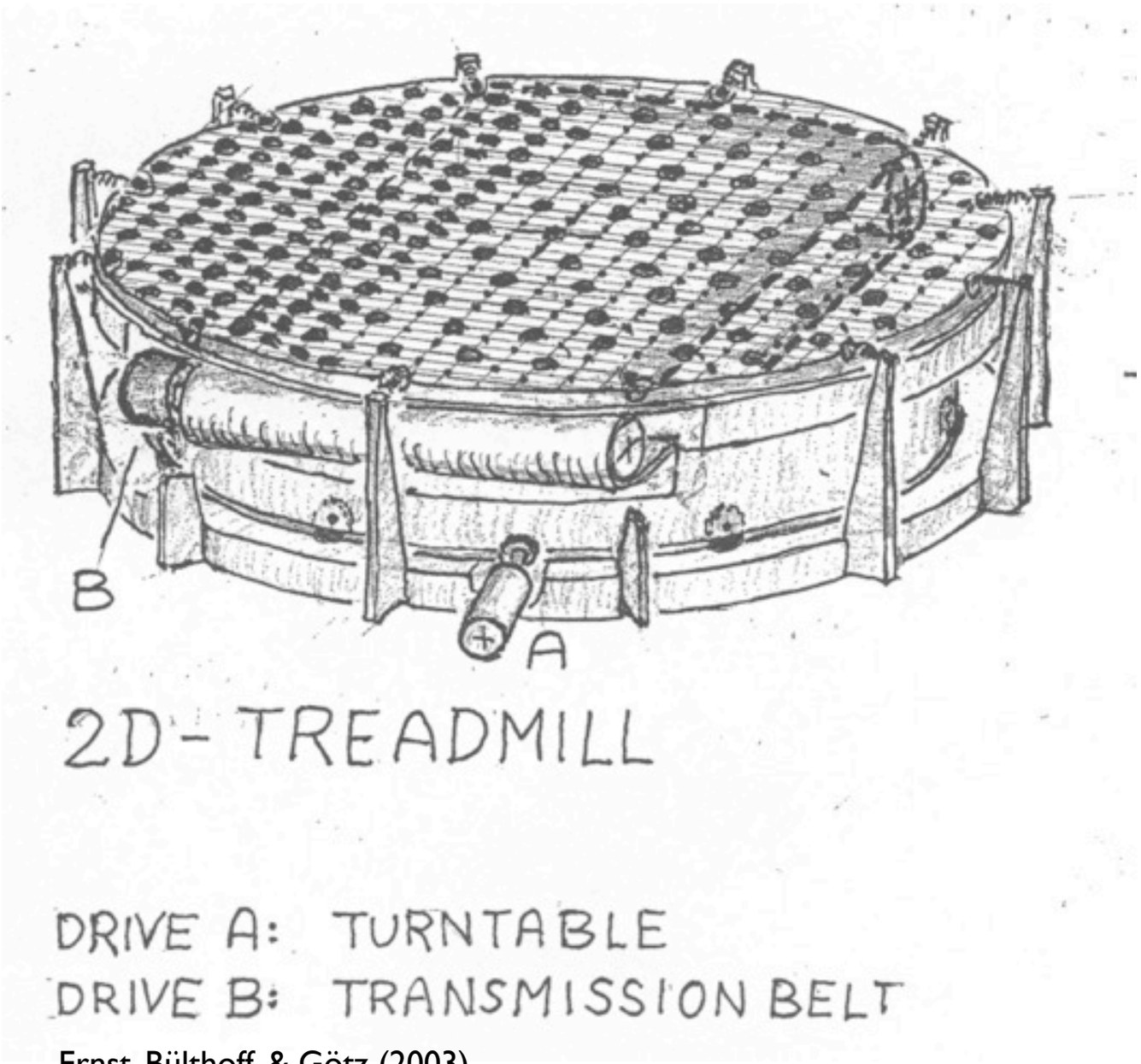
Souman, Frissen, Sreenivasa & Ernst, ***Current Biology*** (2009)

Accumulation of Noise

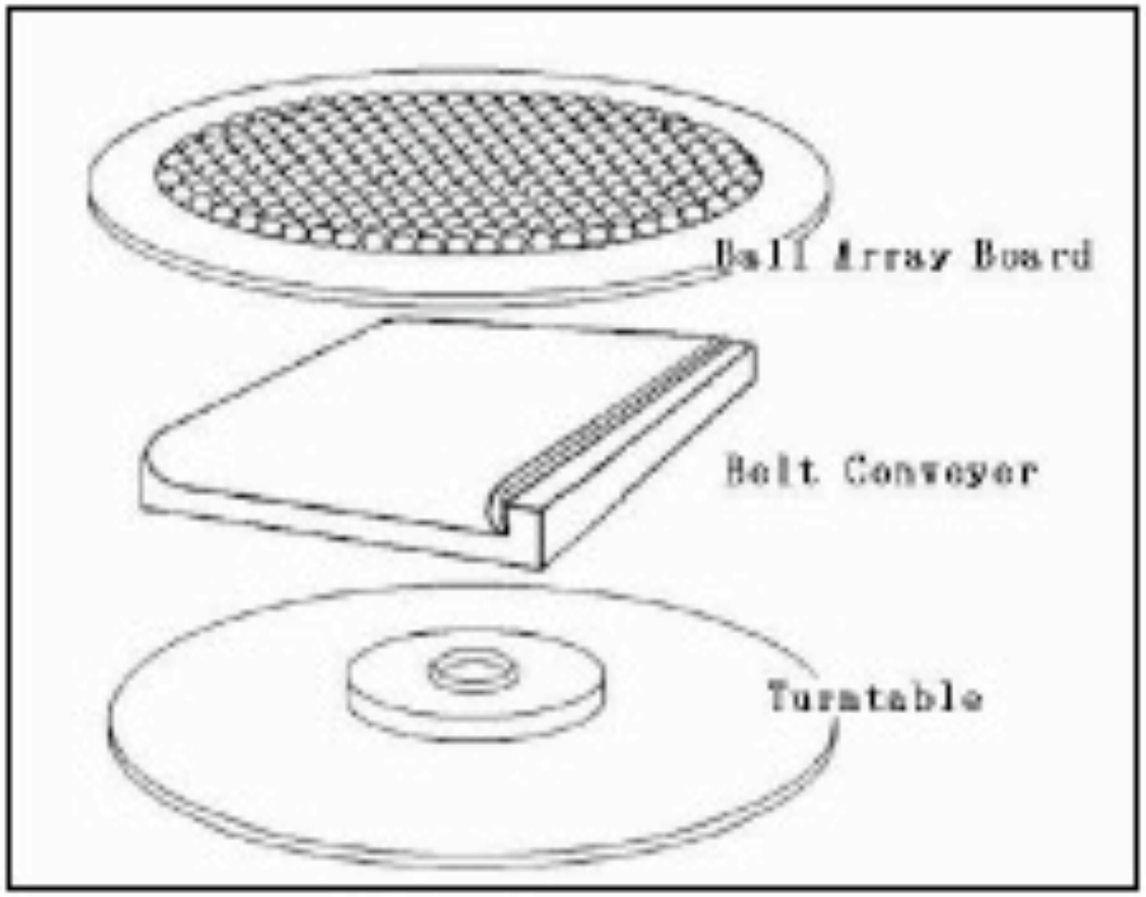




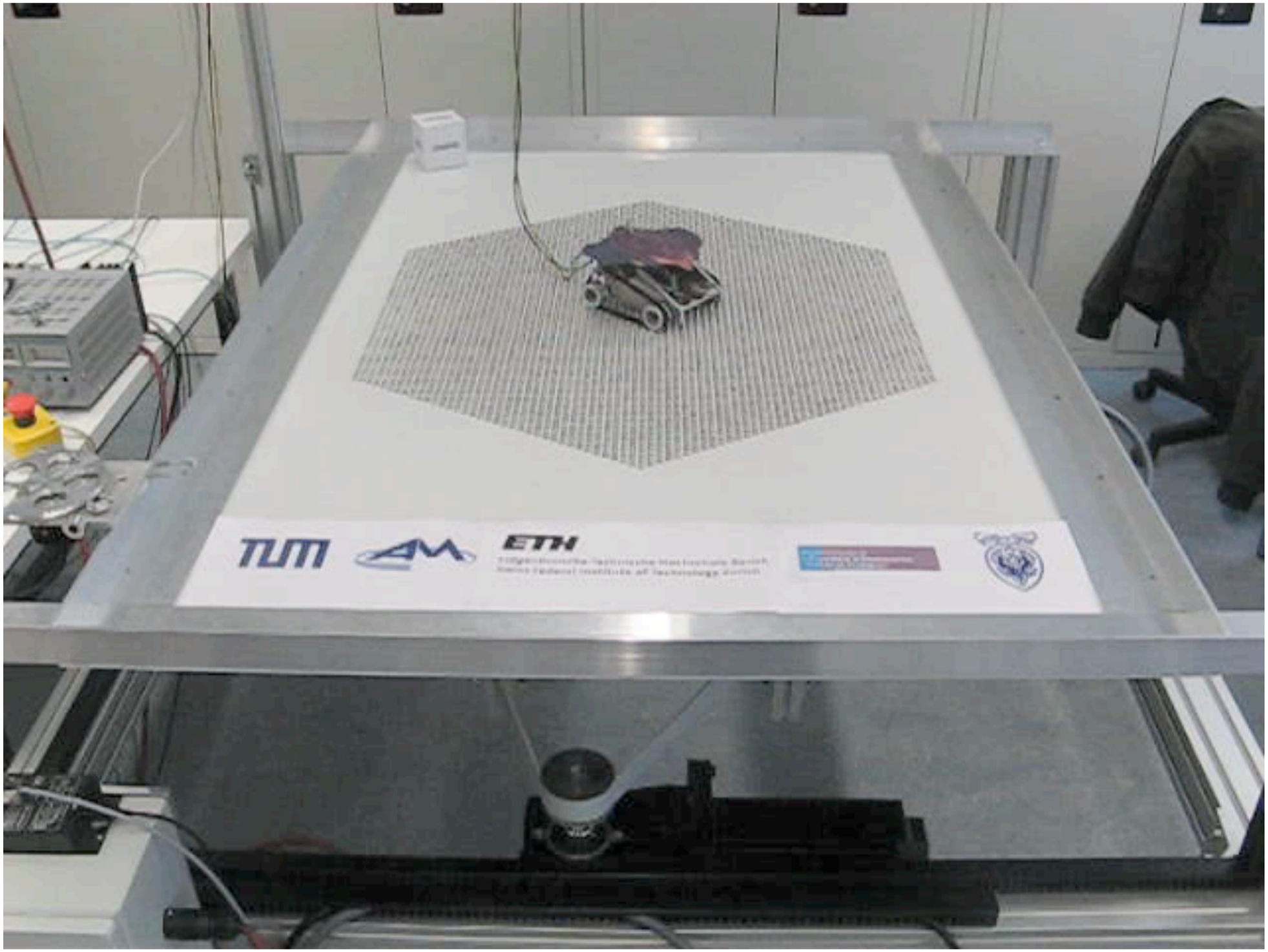
- **The vestibular system accumulates noise when integrating rotation rate into a direction estimate.**
- **This bias is automatically calibrated when external directional cues, e.g. from vision or touch, are available.**

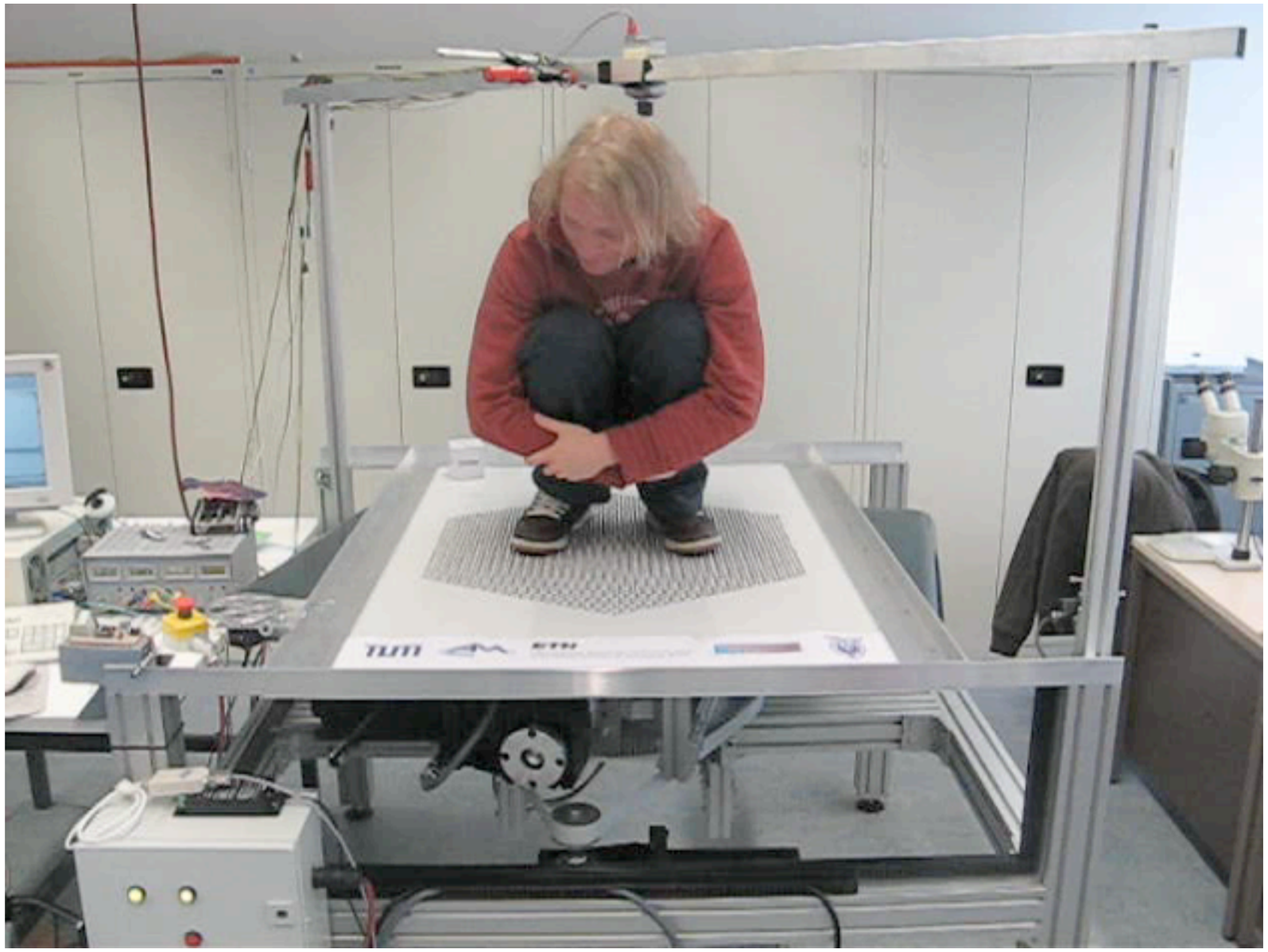


Ernst, Bülthoff, & Götz (2003)

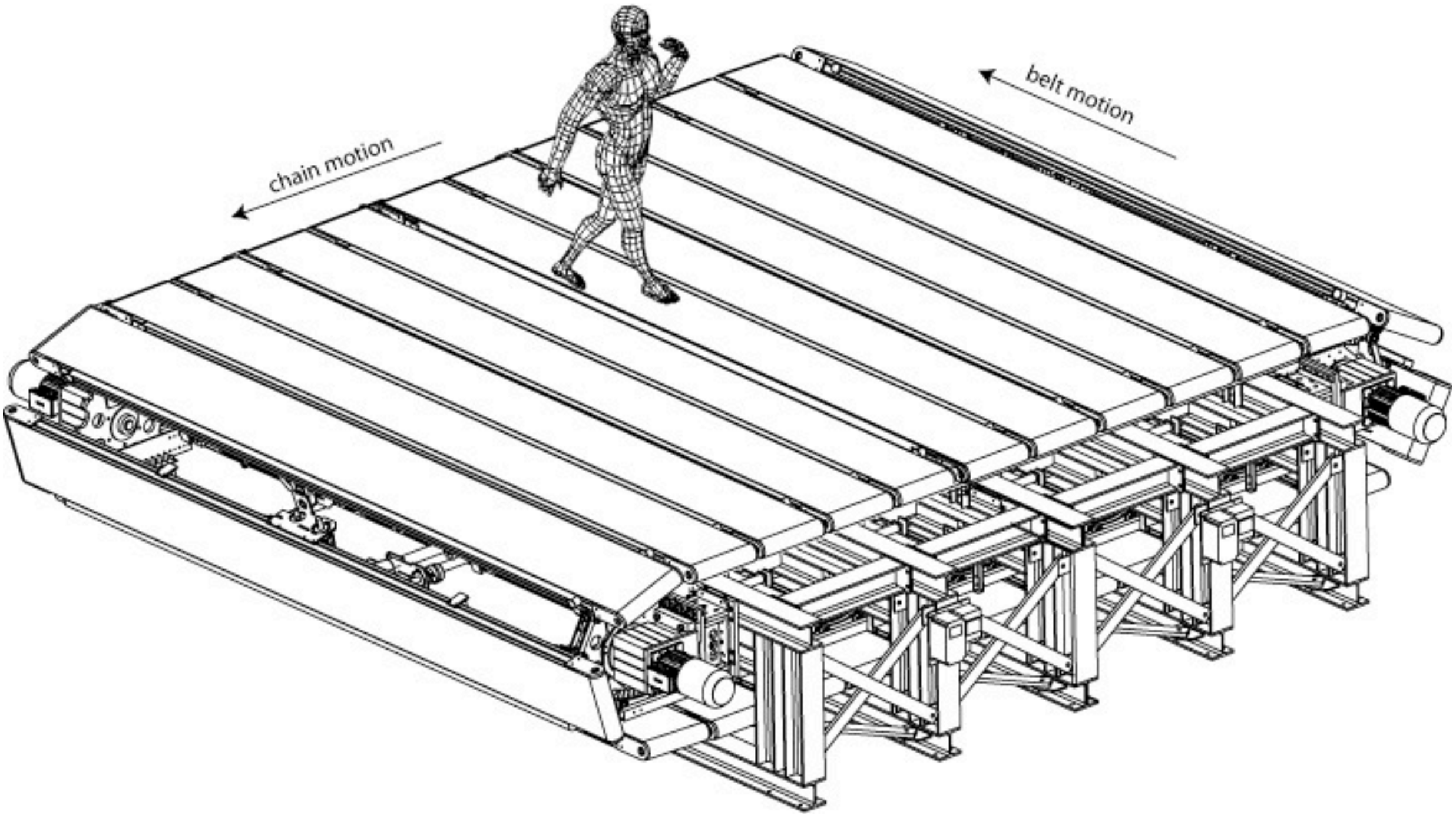


Nagamori, Wakabayashi, & Ito (2005)


TUM
ETH



CyberWalk



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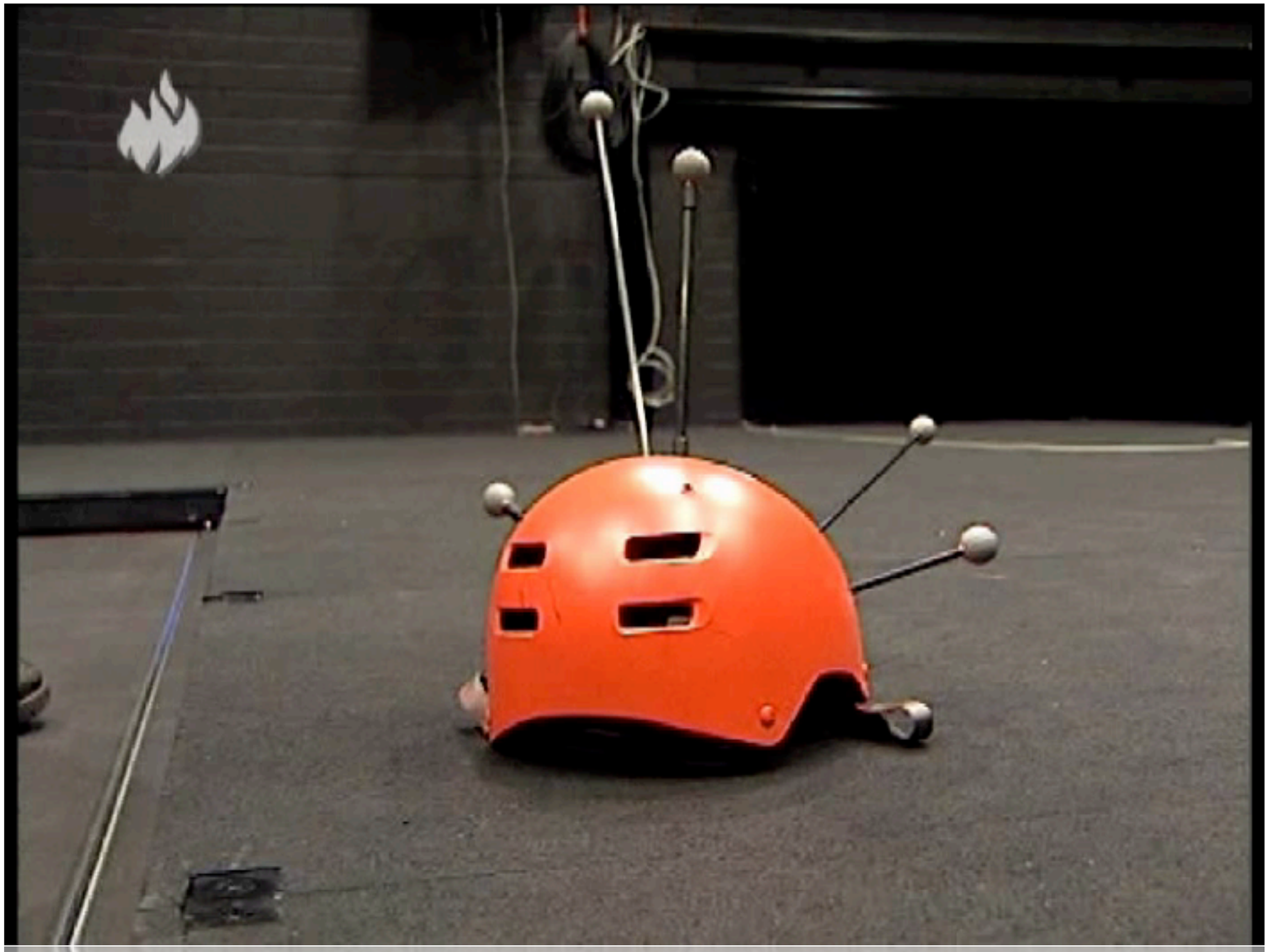
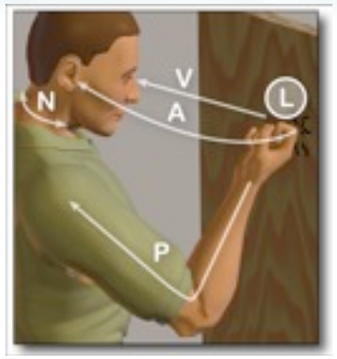


Conclusions



- The brain integrates multisensory information in a **statistically optimal** fashion, taking the variance of the signals into account.

Acknowledgments

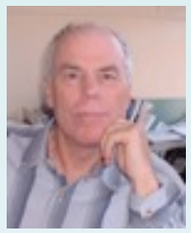
Collaborators

Massimiliano **Di Luca**

Tonja **Machulla**

Wendy **Adams**

Jan **Souman**



Marty **Banks**

Erich **Graf**

Ilja **Frissen**

Johannes **Burge**

Frank **Jäkel**

Manish **Sreenivasa**

Benjamin **Backus**

Martin **Schwaiger**

Grants

IMMERSENCE

TOUCH HapSys

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NEUROKOGNITIVE MECHANISMEN UND IHRE FLEXIBILITÄT

Thank you !!!

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Integration Model