A vestibular sensation: probabilistic approaches to spatial perception

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Introduction

- Organ in the inner ear, provides (sixth) sense – balance and orientation.
- No distinct conscious vestibular sense b/c there is no vestibular cortex.
  - Response found in many cortical fields no evidence for hierarchical organization
- This paper: review studies about system + multisensory integration w/ SDT, Bayes Law
Introduction

- Three spatial orientations functions to describe in detail:
  - 1. Perception of self-motion
  - 2. Perception of tilt
  - 3. Role of vestibular signals in visuospatial updating & maintenance of spatial consistency.

- First summarizes main cortical areas that process vestibular information
Representation of vestibular information in cortex

- Vestibular info → extrastriate cortex/MSTd
- Vestibular info + Optic info → VIP
  - Respond to somatosensory stimulation, signals highly convergent as early as vestibular nucleus
- Imaging studies: large cortical involvement in representing vestibular info, but may overstate range of representation
  - In particular, with somatosensory/proprioceptive sys, might evoke postural and oculomotor responses
Representation of vestibular information in cortex

- Most previous studies have been of passive vestibular stimulation whereas studies of other sensory systems have been active.
- Active tasks have now begun to be used to investigate neural bases of heading perception.
Bayesian framework for multisensory perception

\[
P(X | s_1, s_2) = \frac{P(s_1 | X) P(s_2 | X) P(X)}{P(s_1) P(s_2)} \\
\text{(normalization)}
\]

EG: \(X\) – head direction, \(s_1\) – vestibular info, \(s_2\) – Optic flow
\(s_1\ & s_2\sim\) firing rates from populations of neurons.

[Equation 1]
Bayesian framework for multisensory perception

- Framework predicts cue integration, is behaviorally testable, but computationally demanding.

- Two assumptions to simplify computation:
  - 1. Uniform prior.
    
      - Removes prior from computation; product of likelihoods
  - 2. Gaussian likelihood (has mean and variance)
Bayesian framework for multisensory perception

\[ S'_{\text{BIMODAL}} = w_1 S'_1 + w_2 S'_2 \]

\[
\begin{align*}
    w_1 &= \frac{1/\sigma_1^2}{1/\sigma_1^2 + 1/\sigma_2^2} \\
    w_2 &= \frac{1/\sigma_2^2}{1/\sigma_1^2 + 1/\sigma_2^2}
\end{align*}
\]

[Equation 2]
Bayesian framework for multisensory perception

$$\sigma^2_{\text{BIMODAL}} = \frac{\sigma_1^2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2}$$

[Equation 3]
Bayesian framework for multisensory perception
Visual and Vestibular Cue Integration for Heading Perception

- Empirical predictions for the bimodal signal have been tested with a 2AFC task.
- Thresholds for response were significantly smaller for bimodal vs single modal cues.
- Demonstrates that macaques combine vestibular and visual self-motion cues near-optimally
Visual and Vestibular Cue Integration for Heading Perception, study 2

- When put in conflict, visual and vestibular cues were re-weighed after each trial, such that bimodal perception was biased towards the most reliable cue, just as the model predicts.
- Subjects demonstrated both optimal integration and switching between unimodal captures based on heavily differing reliability: this disambiguated some longstanding controversy.
Visual and Vestibular Cue Integration for Heading Perception

- Real motion vs visual input were alternatingly reported to dominate in various studies.
- This suggested that visual/vestibular convergence involves complicated interactions, and that weights are determined by the severity of the disagreement between the two modalities.
- Optimal cue integration as described is a more tractable alternative.