

Attention and Perception

Lecture 1: Subjective Perception

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Information and Economic Choices

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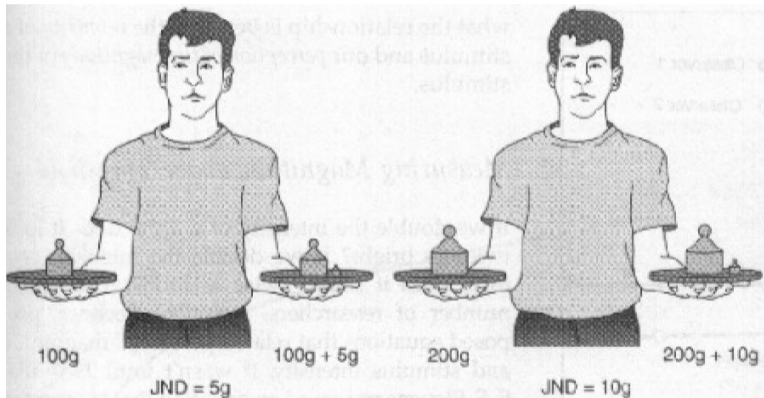
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Modeling Challenge

- ▶ The simplest model of information search in decision-making is item-by-item search (Caplin, Dean & Martin 2011)
- ▶ What to do when item-by-item search is not the appropriate model?
- ▶ Could try other forms of information search
 - ▶ Such as characteristic-by-characteristic search
- ▶ But probably need a fuzzier model of **subjective perception**

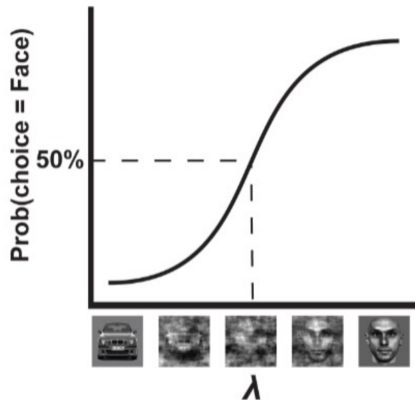
- ▶ Weber (1834) reports one of the first modern perception experiments



Weber and Perception

- ▶ Weber found the point of just noticeable difference (JND)
- ▶ Believed that it was approximately constant
- ▶ Theoretical grounding provided by Gustav Fechner (Weber-Fechner law) (Fechner 1860)
- ▶ Good approximation:
 - ▶ Brightness of lights
 - ▶ Intensity and the pitch of sounds
- ▶ Bad approximation:
 - ▶ Wavelength of light
- ▶ Testable implications of JND in consumption provided by Dziewulski (2020)

- ▶ Gradual nature of JND illustrated by “psychometric” curves



From Antonio Rangel

State-Dependent Stochastic Choice Data

- ▶ Key insight from psychometric analysis: choices are inherently stochastic and state dependent
- ▶ Examples:
 - ▶ Probability chose left hand when heavier weight is in the left hand
 - ▶ Probability detect blue when the circle is $X\%$ blue
 - ▶ Probability say dots moving left when the dots are moving left

Perception Today

- ▶ In psychology and neuroscience, subjective perception continues to be central
 - ▶ See McFadden (1999) review
- ▶ Canonical perception task is moving dots or coherent motion task
 - ▶ For example Roitman & Shadlen (2002)
- ▶ Guess which direction dots are moving on a screen (*left or right*)
 - ▶ Ask monkeys (juice rewards) or humans
- ▶ Only some proportion of the dots move in a coherent direction

[Click here for example](#)

Perception Today

- ▶ How do psychologists and neuroscientists analyze subjective perception of dots?
- ▶ Assume model (functional form) of how decision makers perceive the dots
 - ▶ Leading models: drift diffusion model, race model, signal detection theory
- ▶ Estimate model parameters from observables
 - ▶ Choices, brain activity, decision times, eye-tracking, etc.

Perception Today

- ▶ Standard assumptions for models of subjective perception:
 - ▶ Decision makers get evidence/signals about the world
 - ▶ Update prior beliefs according to Bayes' Rule
 - ▶ Use posterior beliefs to maximize expected value/utility
- ▶ Also standard in economics, computer science, information theory, etc.
- ▶ Will consider deviations later in class
- ▶ But for now, we stay on the main road for models of subjective perception
 - ▶ We will consider it as an “as if” model of how decision-makers process readily-available information

Subjective Perception and Economic Decision Making

- ▶ There are many facts about the world that can be payoff-relevant
 - ▶ Fundamentals of a stock, the effectiveness of a vaccine, characteristics of a health plan, etc.
- ▶ Increasing evidence that individuals can be poorly informed about these facts when making consequential decisions
- ▶ Many reasons why poorly informed:
 - ▶ Only receive partial information from firms or policymakers
 - ▶ Only internalize some of the available information
 - ▶ Only recall some of this information at moment of choice

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Perspective, Approach, Questions

- ▶ My co-authors and I take the perspective of an econometrician who only observes a decision maker's (DM's) choices, not how well informed they are
- ▶ Why? Because the DM's perception is **subjective** (the information that is internalized is **private**)
- ▶ We employ an “information-theoretic revealed preference” approach
 - ▶ Assume standard information theory framework: correct prior → signal realization → update beliefs correctly → maximize expected utility
 - ▶ But treat utility, signals, and beliefs as unobservable!
- ▶ Key questions:
 - ▶ Consistency: *As if* the DM chooses optimally given some private information?
 - ▶ Recovery: What does the DM value and how valuable is their private information?

Caplin & Martin (2015), "A Testable Theory of Imperfect Perception."

- ▶ Question: Can we assume that a decision maker is **updating beliefs correctly** (using Bayes' Rule) and **maximizing utility** for unobservable private information?
 - ▶ Key assumptions behind many, if not most, models of perception
 - ▶ Includes: drift diffusion model, race model, signal detection theory
 - ▶ Also captures unobserved persuasion (not know what advisor says to client)
- ▶ Use choice data (observable) to understand private information (unobservable)

- ▶ In other words: We consider an econometrician who wants to determine if a decision maker chose optimally given some private information, but only knows the actions taken, and nothing about information obtained
- ▶ For example, all the econometrician might know about the decision-maker's information is that it produces the following joint distribution over actions (a_1, a_2) and states (ω_1, ω_2)

$$P = \begin{matrix} & \begin{matrix} \omega_1 & \omega_2 \end{matrix} \\ \begin{pmatrix} .4 & .1 \\ .1 & .4 \end{pmatrix} & \begin{matrix} a_1 \\ a_2 \end{matrix} \end{matrix}$$

Examples of P

- ▶ Probability buy a stock when it has certain fundamentals
- ▶ Probability PPO health plan is chosen when it has certain benefits
- ▶ Probability buy fresh bread when packaged bread is at a certain price
- ▶ Probability hire an employee who will be rated highly
- ▶ Probability make a loan to someone who will default
- ▶ Probability ordering a test for someone who has a disease
- ▶ Common elements: State impacts prizes, decision maker may not be fully informed about state, analyst knows state given data or time

Knowns

- ▶ Example:

$$P = \begin{matrix} & \omega_1 & \omega_2 \\ \begin{pmatrix} .4 & .1 \\ .1 & .4 \end{pmatrix} & a_1 \\ & a_2 \end{matrix}$$

- ▶ Actions A (finite)
- ▶ States Ω (finite)
- ▶ P : Joint distribution of actions and states
 - ▶ $P(a, \omega)$ is the probability of taking action a and being in state ω
 - ▶ Objective prior over states given by $P(\omega)$
 - ▶ Assume all actions chosen to avoid minutiae
 - ▶ Note: Caplin & Martin (2015) (CM15 hereafter) uses q instead of P

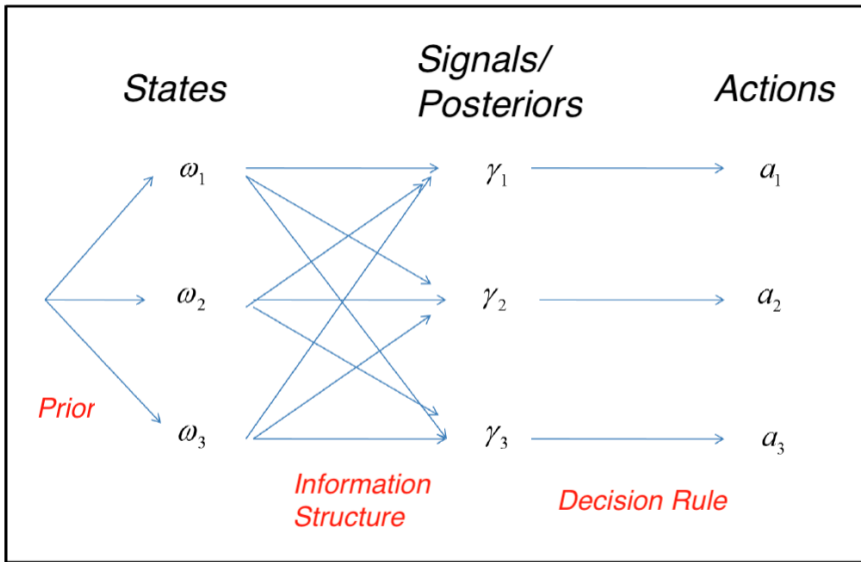
Possibly known

- ▶ Prizes X
 - ▶ $x(a, \omega) \in X$ is the prize from taking action a in state ω
 - ▶ Utility function defined over this set: $u : X \rightarrow \mathbb{R}$
 - ▶ Note: Caplin & Dean (2015) (CD15 hereafter) and Caplin, Dean & Leahy (2022) (CDL22 hereafter) use compact $a(\omega)$
- ▶ Example: Good prize for matching state to action (tracking problem)

$$x(a, \omega) = \begin{pmatrix} \omega_1 & \omega_2 \\ x_G & x_B \\ x_B & x_G \end{pmatrix} \begin{matrix} a_1 \\ a_2 \end{matrix} \quad \text{so can normalize to} \quad u = \begin{pmatrix} \omega_1 & \omega_2 \\ 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{matrix} a_1 \\ a_2 \end{matrix}$$

- ▶ If prizes are unknown, WLOG to assume that a distinct prize is obtained from taking each action in each state

- ▶ Unknown (not observed):
 1. **Utility function** $u : X \rightarrow \mathbb{R}$
 - ▶ X is the set of prizes, and $x(a, \omega)$ is the prize from taking action a in state ω
 2. **Subjective prior** $\mu : \Omega \rightarrow (0, 1)$
 - ▶ Note: CM15 and CD15 assume this is observable
 3. **Information structure** $\pi : \Omega \rightarrow \Delta(\Gamma)$
 - ▶ “Posterior-based” approach of Bayesian persuasion (Kamenica & Gentzkow 2011): π maps into distributions of posteriors $\gamma \in \Gamma$
 - ▶ Can think of these posteriors as being generated by an underlying signal structure S
 - ▶ $\pi(\gamma|\omega)$ is the probability of posterior γ in state ω
 - ▶ $\pi(\gamma)$ is the unconditional probability of posterior γ
 - ▶ Note: CDL22 use Q and call “attention strategy”
 4. **Decision rule** $\sigma : \Gamma \rightarrow \Delta(A)$
 - ▶ $\sigma(a|\gamma)$ probability of action a given posterior γ
 - ▶ Note: CM15 and CD15 use C and call “choice function”, CDL22 use q and call “action strategy”



Consistency

- ▶ Question: Is a given P “consistent” with Bayes’ Rule and expected utility maximization (BEU)?
- ▶ In other words, do there exist unobservables (u, μ, π, σ) that could explain what we see in P and are in line with Bayes’ Rule and expected utility maximization?
- ▶ Exercise: Find (u, μ, π, σ) that could explain what we see in this P and are in line with Bayes’ Rule and expected utility maximization in this tracking problem

$$u = \begin{array}{cc} \omega_1 & \omega_2 \\ \left(\begin{array}{cc} 1 & 0 \\ 0 & 1 \end{array} \right) & \begin{array}{l} a_1 \\ a_2 \end{array} \end{array} \quad \& \quad P = \begin{array}{cc} \omega_1 & \omega_2 \\ \left(\begin{array}{cc} .4 & .1 \\ .1 & .4 \end{array} \right) & \begin{array}{l} a_1 \\ a_2 \end{array} \end{array}$$

Consistency

- ▶ For a utility function u , it's easy to assess if data P is not consistent with the model
- ▶ **Not** consistent if can improve utility by making a *wholesale* switch from any chosen action to another action
 - ▶ In other words, if can improve utility by switching to action a_2 at all posteriors where chose action a_1
 - ▶ This means that whatever the decision rule is, it doesn't maximize expected utility
- ▶ The following simple example illustrates

► Example:

$$u = \begin{pmatrix} \omega_1 & \omega_2 \\ 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{matrix} a_1 \\ a_2 \end{matrix} \quad \& \quad P = \begin{pmatrix} \omega_1 & \omega_2 \\ .1 & .4 \\ .4 & .1 \end{pmatrix} \begin{matrix} a_1 \\ a_2 \end{matrix}$$

- For this utility function, P is not consistent with any information structure
- Why? Can improve utility by making a *wholesale* switch to choosing a_2 when chose a_1
 - When chose a_1 , got 1 with unconditional probability .1, but if had chosen a_2 instead, could have got 1 with unconditional probability .4
- Now introduce general version of above logic: restrictions ensuring no utility increase from making wholesale switch from any chosen action

Definition

(u, μ, π, σ) is a **BEU representation** of P if it satisfies:

1. Data Matching¹:

$$P(a, \omega) = \mu(\omega) \sum_{\gamma \in \Gamma} \pi(\gamma|\omega) \sigma(a|\gamma)$$

2. Bayesian Updating:

$$\gamma(\omega) = \frac{\mu(\omega) \pi(\gamma|\omega)}{\sum_{v \in \Omega} \mu(v) \pi(\gamma|v)}$$

3. Maximization: If $\pi(\gamma) > 0$ and $\sigma(a|\gamma) > 0$,

$$\sum_{\omega \in \Omega} \gamma(\omega) u(x(a, \omega)) \geq \sum_{\omega \in \Omega} \gamma(\omega) u(x(b, \omega))$$

¹Note that Data Matching implies correct subjective prior.

Definition

Utility function u satisfies the No Improving Action Switches (**NIAS**) condition with respect to P if,

$$\sum_{\omega \in \Omega} P(a, \omega) u(x(a, \omega)) \geq \sum_{\omega \in \Omega} P(a, \omega) u(x(b, \omega)),$$

for all $a, b \in A$.

Intuition: Cannot improve utility by making a *wholesale* switch from any chosen action

Theorem

P has a BEU representation if and only if there exists $u : X \rightarrow \mathbb{R}$ satisfying the NIAS inequalities.

Note: To rule out global indifference, just require the inequality to be strict for some $a, b \in A$ in Maximization and NIAS

▶ Illustration of NIAS inequalities:

▶ Tracking problem:

$$u = \begin{pmatrix} \omega_1 & \omega_2 \\ 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{matrix} a_1 \\ a_2 \end{matrix}$$

▶ 75% prior probability of state 1 (ω_1)

▶ Choose correctly around 55% of the time in both states (a_1 in ω_1 and a_2 in ω_2)

▶ Pause: Can we model this decision maker as updating beliefs correctly and maximizing expected utility given their imperfect perception?

▶ **NIAS shows cannot be updating beliefs correctly and maximizing expected utility given imperfect perception!**

▶ Whoa! How did we get there?

▶ Recall no EU improvement from switching from action a to action b :

$$\sum_{\omega \in \Omega} P(a, \omega) u(x(a, \omega)) \geq \sum_{\omega \in \Omega} P(a, \omega) u(x(b, \omega))$$

▶ NIAS are simply:

$$\text{For action } a_1 : P(a_1, \omega_1) \geq P(a_1, \omega_2)$$

$$\text{For action } a_2 : P(a_2, \omega_2) \geq P(a_2, \omega_1)$$

▶ Or:

$$\text{For action } a_1 : P(a_1|\omega_1)P(\omega_1) \geq P(a_1|\omega_2)P(\omega_2)$$

$$\text{For action } a_2 : P(a_2|\omega_2)P(\omega_2) \geq P(a_2|\omega_1)P(\omega_1)$$

▶ In this example:

$$\text{For action } a_1 : .55 * .75 \geq .45 * .25$$

$$\text{For action } a_2 : .55 * .25 \not\geq .45 * .75$$

- ▶ NIAS provides simple test for optimal choice with private information
 - ▶ Look for solution to a set of linear inequalities
 - ▶ Easier to implement than test of Lu (2016)
- ▶ NIAS has been tested in lab experiments using perception tasks (later)
 - ▶ Sums of numbers (Dean & Neligh 2023, Almog & Martin 2024)
 - ▶ Proportion of colored balls (Dean & Neligh 2023, de Clippel & Rozen 2021)
 - ▶ Number of balls and types of angles (Dewan & Neligh 2020)
 - ▶ Counting shapes (Caplin, Csaba, Leahy & Nov 2020)
- ▶ Was tested in real-world setting with limited data by Rambachan (2024)
- ▶ Was extended to settings without state observability by Rehbeck (2023)

- ▶ Theoretical applications in Caplin & Martin (2015):
 1. Utility recovery
 - ▶ In subsequent JPE paper, provide the convex geometry to actually do this (Caplin & Martin 2021)
 2. Robust predictions
 - ▶ Conceptually and technically related to robustness agenda of Bergemann and Morris (Bergemann & Morris 2013, 2016)
 3. Model classification
 - ▶ Example: Can Logit model be explained with imperfect perception?

- ▶ Consider a standard tracking problem with actions: $\{l,r\}$ and states: $\{L,R\}$:

$$u = \begin{matrix} & \omega_1 = L & \omega_2 = R \\ \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} & a_1 = l \\ & a_2 = r \end{matrix}$$

- ▶ Pause: Can you work out the NIAS conditions for this setting?
- ▶ Recall no EU improvement from switching from action a to action b :

$$\sum_{\omega \in \Omega} P(a, \omega) u(x(a, \omega)) \geq \sum_{\omega \in \Omega} P(a, \omega) u(x(b, \omega))$$

- ▶ They are simply:

For action l : $P(l, L) \geq P(l, R)$

For action r : $P(r, R) \geq P(r, L)$

- ▶ Logit generates the following data:

$$P(I|L) = \frac{e^{\frac{1}{\lambda}}}{1 + e^{\frac{1}{\lambda}}} \quad \& \quad P(I|R) = \frac{1}{1 + e^{\frac{1}{\lambda}}}$$

- ▶ Pause: Can you work out the implications given NIAS?
- ▶ They are:

$$\frac{e^{\frac{1}{\lambda}}}{1 + e^{\frac{1}{\lambda}}} P(L) \geq \frac{1}{1 + e^{\frac{1}{\lambda}}} (1 - P(L))$$
$$\frac{e^{\frac{1}{\lambda}}}{1 + e^{\frac{1}{\lambda}}} (1 - P(L)) \geq \frac{1}{1 + e^{\frac{1}{\lambda}}} P(L)$$

- ▶ For $P(L) \neq 1/2$, NIAS shows Logit model can be explained with imperfect perception if and only if,

$$\lambda \leq \frac{1}{\left| \ln \left(\frac{P(L)}{1-P(L)} \right) \right|}$$

Costly Attention Applications

- ▶ NIAS is also a foundational condition for models of costly attention
 - ▶ If and only if condition for choosing optimally given chosen attention
- ▶ NIAS+NIAC \Leftrightarrow rational inattention (Caplin & Dean 2015) (later)
- ▶ NIAS+GACI \Leftrightarrow non-separable costs (Chambers, Liu & Rehbeck 2020)
- ▶ NIAS+Axiom 3 \Leftrightarrow posterior-separable costs (Denti 2022)

Open Questions

- ▶ NIAS w/ unobservable preference heterogeneity
 - ▶ Analogous to recent work on unobservable preferences and consideration sets
 - ▶ Make falsifiable by putting functional form restrictions on preferences and/or by restricting to a class of problems?
 - ▶ Challenge for NIAS: Can characterize restrictions for each posterior, but cannot cleanly aggregate over unobserved posteriors that generate same action
 - ▶ Could also put assumptions on prior and/or costs of information (link w/ Brown & Jeon (2024))
- ▶ NIAS with belief biases (link w/ de Clippel & Zhang (2022))
 - ▶ Need either if NIAS fails or if in setting where belief biases are plausible
 - ▶ For example, incorrect priors/stereotyping in discrimination work

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