

# Latent Trait Measurement Models for Other (not Binary) Responses

## Today's Topics:

- Review of generalized models for categorical outcomes
- Ordered Categories → Graded Response
- Maybe Ordered Categories → Partial Credit
- Unordered Categories → Nominal Response
- Count Outcomes → Poisson and Negative Binomial
- Too many Zeros Outcomes → Zero-Inflated/Hurdle/Two-Part

# Our Friend the Logit

- The **logit** is also the basis for many other generalized models for predicting categorical outcomes
- Next we'll see how  $C$  possible response categories can be predicted using  $C - 1$  binary “submodels” that involve carving up the categories in different ways, in which each binary submodel uses a logit link to predict its outcome
- Types of categorical outcomes:
  - Definitely ordered categories: “**cumulative logit**”
  - Maybe ordered categories: “**adjacent category logit**” (not used much)
  - Definitely NOT ordered categories: “**generalized logit**”

# Logit-Based Models for $C$ Ordinal Categories

- Known as “cumulative logit” or “proportional odds” model in generalized models; will be known as “graded response model” in IRT
  - LINK=CLOGIT, DIST=MULT in SAS GLIMMIX
- Models the probability of **lower vs. higher** cumulative categories via  $C - 1$  submodels (e.g., if  $C = 4$  possible responses of  $c = 0,1,2,3$ ):

**0** vs. **1, 2, 3**  
Submodel<sub>1</sub>

**0,1** vs. **2,3**  
Submodel<sub>2</sub>

**0,1,2** vs. **3**  
Submodel<sub>3</sub>

I've named these submodels based on what they predict, but programs will use their own names in the output.

- In SAS, what the binary submodels predict depends on whether the model is predicting **DOWN** ( $y_i = 0$ , the default) or **UP** ( $y_i = 1$ ) cumulatively
- **Example predicting UP in an empty model (subscripts=parm,submodel)**
- Submodel 1:  $\text{Logit}(y_i > 0) = \beta_{01} \rightarrow p(y_i > 0) = \exp(\beta_{01})/[1 + \exp(\beta_{01})]$
- Submodel 2:  $\text{Logit}(y_i > 1) = \beta_{02} \rightarrow p(y_i > 1) = \exp(\beta_{02})/[1 + \exp(\beta_{02})]$
- Submodel 3:  $\text{Logit}(y_i > 2) = \beta_{03} \rightarrow p(y_i > 2) = \exp(\beta_{03})/[1 + \exp(\beta_{03})]$

# Logit-Based Models for $C$ Ordinal Categories

- Models the probability of **lower vs. higher** cumulative categories via  $C - 1$  submodels (e.g., if  $C = 4$  possible responses of  $c = 0,1,2,3$ ):

$$\underbrace{0 \text{ vs. } 1,2,3}_{\text{Submodel}_1} \rightarrow \text{Prob}_1$$

$$\underbrace{0,1 \text{ vs. } 2,3}_{\text{Submodel}_2} \rightarrow \text{Prob}_2$$

$$\underbrace{0,1,2 \text{ vs. } 3}_{\text{Submodel}_3} \rightarrow \text{Prob}_3$$

$$\begin{aligned} \text{Logit}(y_i > 2) &= \beta_{03} \\ \rightarrow p(y_i > 2) &= \frac{\exp(\beta_{03})}{1 + \exp(\beta_{03})} \end{aligned}$$

- In SAS, what the binary submodels predict depends on whether the model is predicting **DOWN** ( $y_i = 0$ , the default) or **UP** ( $y_i = 1$ ) cumulatively
  - Either way, the model predicts the middle category responses *indirectly*

- Example if predicting UP with an empty model:**

- Probability of 0 =  $1 - \text{Prob}_1$
- Probability of 1 =  $\text{Prob}_1 - \text{Prob}_2$
- Probability of 2 =  $\text{Prob}_2 - \text{Prob}_3$
- Probability of 3 =  $\text{Prob}_3 - 0$

The cumulative submodels that create these probabilities are each estimated using **all the data** (good, especially for categories not chosen often), but **assume order in doing so** (may be bad or ok, depending on your response format).

# Logit-Based Models for $C$ Categories

- Uses **multinomial distribution for residuals**, whose PDF for  $C = 4$  categories of  $c = 0,1,2,3$ , an observed  $y_i = c$ , and indicators  $I$  if  $c = y_i$

$$f(y_i = c) = p_{i0}^{I[y_i=0]} p_{i1}^{I[y_i=1]} p_{i2}^{I[y_i=2]} p_{i3}^{I[y_i=3]}$$

Only  $p_{ic}$  for the response  $y_i = c$  gets used

- Maximum likelihood is then used to find the most likely parameters in the model to predict the probability of each response through the (usually logit) link function; probabilities sum to 1:  $\sum_{c=1}^C p_{ic} = 1$
- Other models for categorical data that use the multinomial:
  - Adjacent category logit (partial credit): Models the probability of **each next highest** category via  $C - 1$  submodels (e.g., if  $C = 4$ ):  
**0 vs. 1**                      **1 vs. 2**                      **2 vs. 3**
  - Baseline category logit (nominal): Models the probability of **reference vs. other** category via  $C - 1$  submodels (e.g., if  $C = 4$  and  $0 = \text{ref}$ ):  
**0 vs. 1**                      **0 vs. 2**                      **0 vs. 3**

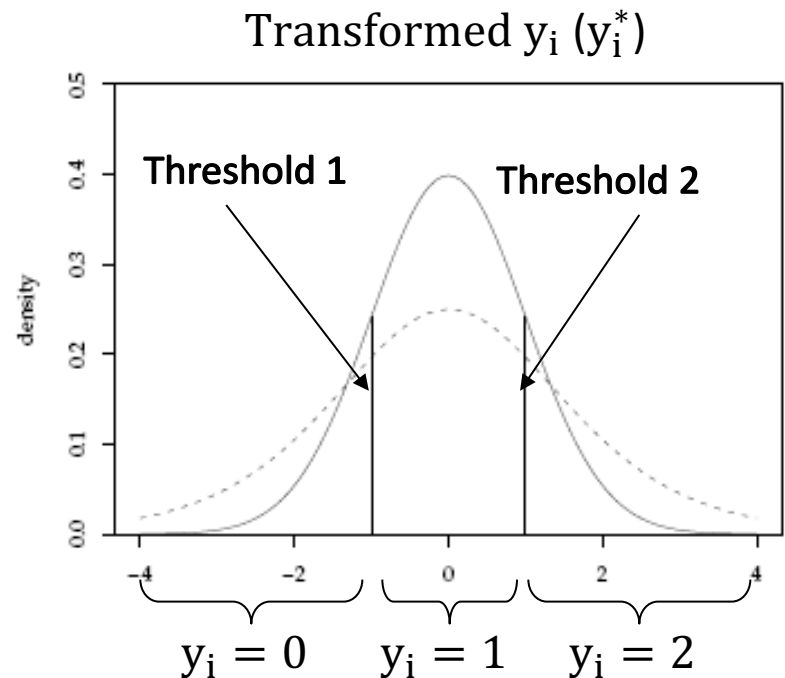
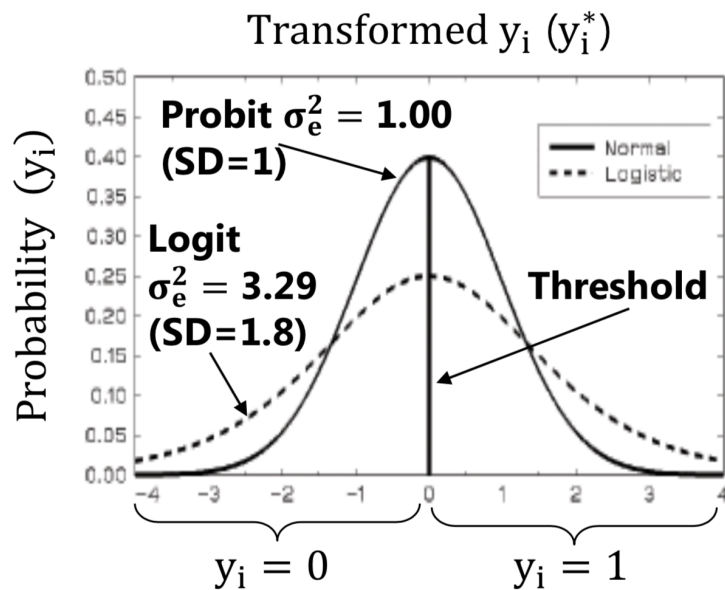
In **nominal** models, all parameters are estimated **separately** per submodel

# Polytomous Items = Categorical Outcomes

- **Polytomous = more than 2 options**
- Polytomous models are not numbered like binary models, but instead get called different names
  - Most have a 1-PL vs. 2-PL version that go by different names
  - Within each, different constraints on what to do with multiple options
- **Three main kinds of polytomous models:**
  - Response options are ordered for sure → Cumulative Logit
    - Graded Response or Modified Graded Response Model (IRT and IFA)
  - Response options may be ordered → Adjacent Category Logit
    - (Generalized) Partial Credit Model or Rating Scale Model (IRT only)
  - No way are these response options ordered → Baseline Category Logit
    - Nominal Response Model (IRT and IFA)

# The Threshold Concept

$$y_i^* = \textit{threshold} + \textit{rest of your model} + e_i$$



- Each categorical variable is **really** the chopped-up version of a pretend underlying continuous variable ( $y^*$ ) with mean = 0 (variance = 1.00 or 3.29)
- Polytomous models will differ in how they make use of multiple thresholds per item in which  $C = \#$  categories, so **# thresholds per item =  $k = C-1$**

# Graded Response Model for Ordinal Categories

- Ideal for items with clear underlying response continuum (e.g., Likert)
- # response options don't have to be the same across items
- GRM is an “indirect” or “difference” model
  - Compute difference between models to get probability of each response
- Estimate 1  $a_i$  per item and  $k = C - 1$  difficulties (4 options  $\rightarrow$  3 difficulties)
- Models the probability of **lower vs. higher** cumulative categories via  $k$  submodels (e.g., if  $C = 4$  possible responses of  $c = 0,1,2,3$ ):

0 vs. 1, 2, 3  
Submodel<sub>1</sub>

0, 1 vs. 2, 3  
Submodel<sub>2</sub>

0, 1, 2 vs. 3  
Submodel<sub>3</sub>

Mplus will refer to these thresholds using \$1, \$2, \$3 after the item name  
Lavaan |t1, |t2, |t3

- Each submodel is estimated using all the data cumulatively (assumes order)
- As with binary items, lavaan and Mplus estimates the IFA model directly (loadings and thresholds), but unlike binary items, it won't do the IRT conversion into discriminations and difficulties (but see my spreadsheet for help)



# Example Graded Response Model (GRM)

IRT version of the GRM: Note that  $a_i$  is the same across submodels...

- **0** vs. **1,2,3**:  $\text{Logit}(y_{is} > 0) = a_i(\theta_s - b_{1i}) \rightarrow p1(y_{is} > 0) = \frac{\exp(a_i(\theta_s - b_{1i}))}{1 + \exp(a_i(\theta_s - b_{1i}))}$
- **0,1** vs. **2,3**:  $\text{Logit}(y_{is} > 1) = a_i(\theta_s - b_{2i}) \rightarrow p2(y_{is} > 1) = \frac{\exp(a_i(\theta_s - b_{2i}))}{1 + \exp(a_i(\theta_s - b_{2i}))}$
- **0,1,2** vs. **3**:  $\text{Logit}(y_{is} > 2) = a_i(\theta_s - b_{3i}) \rightarrow p3(y_{is} > 2) = \frac{\exp(a_i(\theta_s - b_{3i}))}{1 + \exp(a_i(\theta_s - b_{3i}))}$

IFA version of the GRM—what is actually estimated in Mplus:

- **0** vs. **1,2,3**:  $\text{Logit}(y_{is} > 0) = -\tau_{1i} + \lambda_i F_s \rightarrow p1(y_{is} > 0) = \frac{\exp(-\tau_{1i} + \lambda_i F_s)}{1 + \exp(-\tau_{1i} + \lambda_i F_s)}$
- **0,1** vs. **2,3**:  $\text{Logit}(y_{is} > 1) = -\tau_{2i} + \lambda_i F_s \rightarrow p2(y_{is} > 1) = \frac{\exp(-\tau_{2i} + \lambda_i F_s)}{1 + \exp(-\tau_{2i} + \lambda_i F_s)}$
- **0,1,2** vs. **3**:  $\text{Logit}(y_{is} > 2) = -\tau_{3i} + \lambda_i F_s \rightarrow p3(y_{is} > 2) = \frac{\exp(-\tau_{3i} + \lambda_i F_s)}{1 + \exp(-\tau_{3i} + \lambda_i F_s)}$

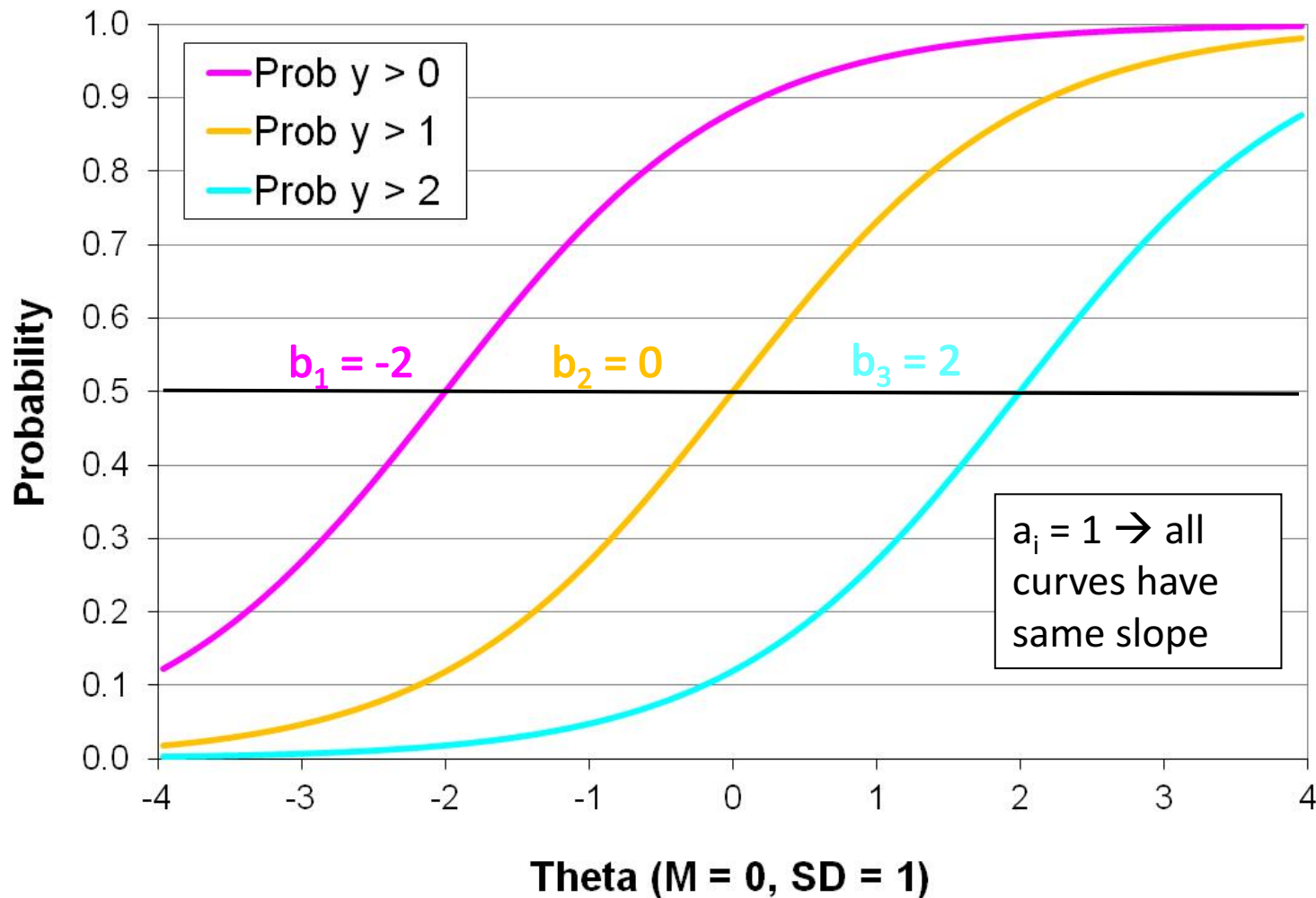
GRM indirectly predicts probability of each category

- $p(y_{is} = 0) = 1 - p1$
- $p(y_{is} = 1) = p1 - p2$
- $p(y_{is} = 2) = p2 - p3$
- $p(y_{is} = 3) = p3 - 0$

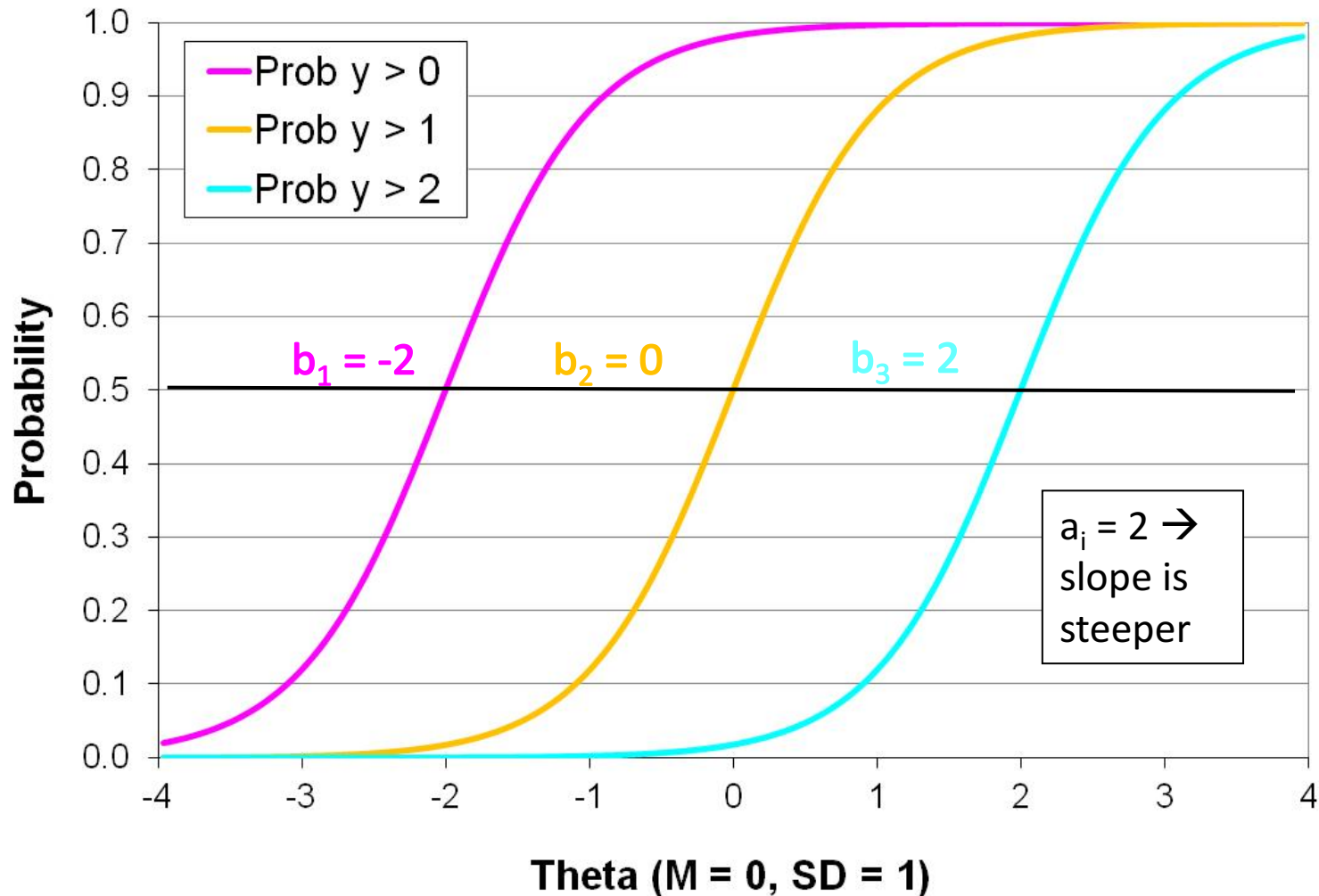
IRT  $b_{ki}$  = trait level needed for a 50% probability (logit = 0) of the **higher binary category**

IFA  $\tau_{ki}$  = logit of the probability of the **lower binary category** when Factor = 0

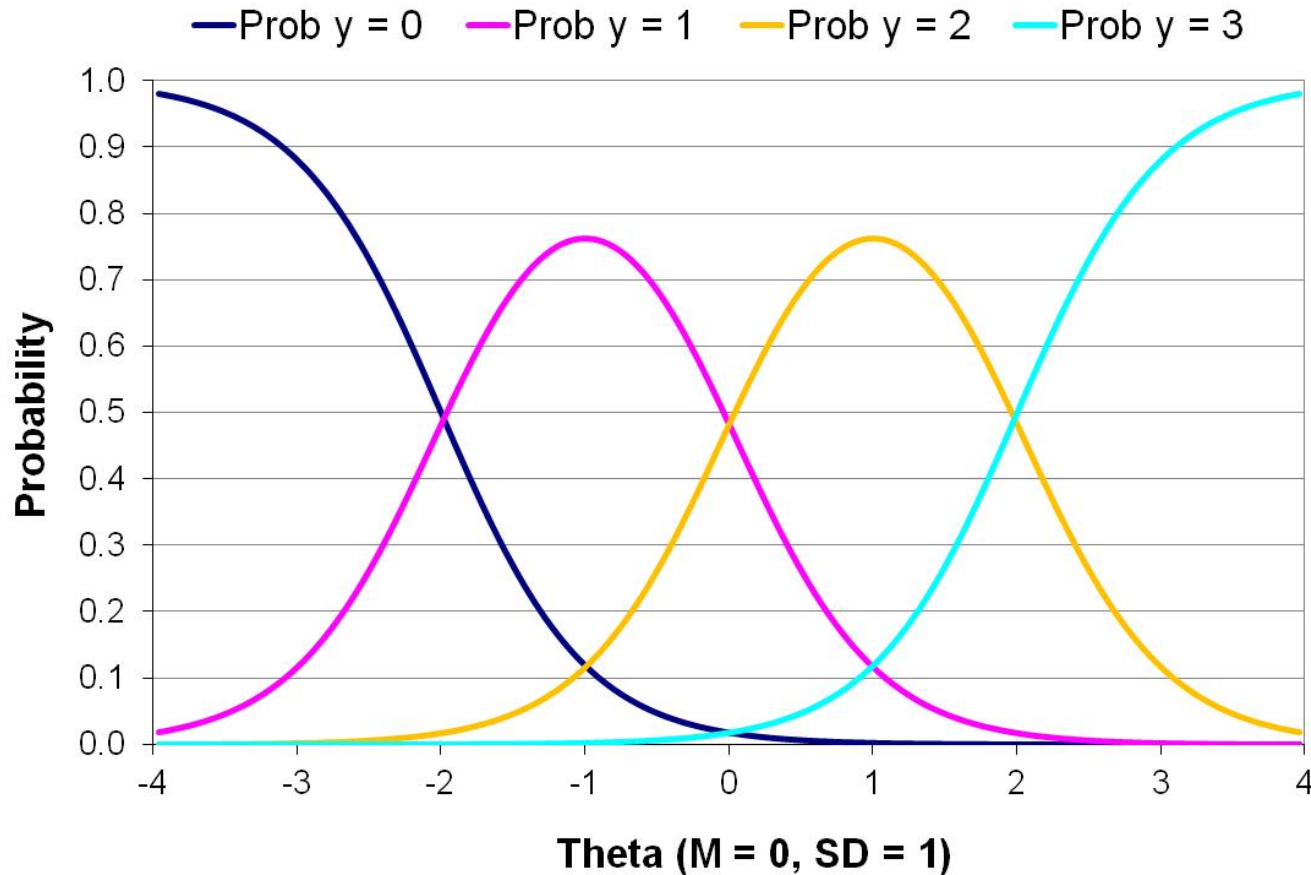
# Cumulative Item Response Curves: GRM for 4-Category (0|23) Item, $a_i=1$



# Cumulative Item Response Curves: GRM for 4-Category (0|23) Item, $a_i=2$



# Category Response Curves: GRM for 4-Category (0|23) Item, $a_i=2$

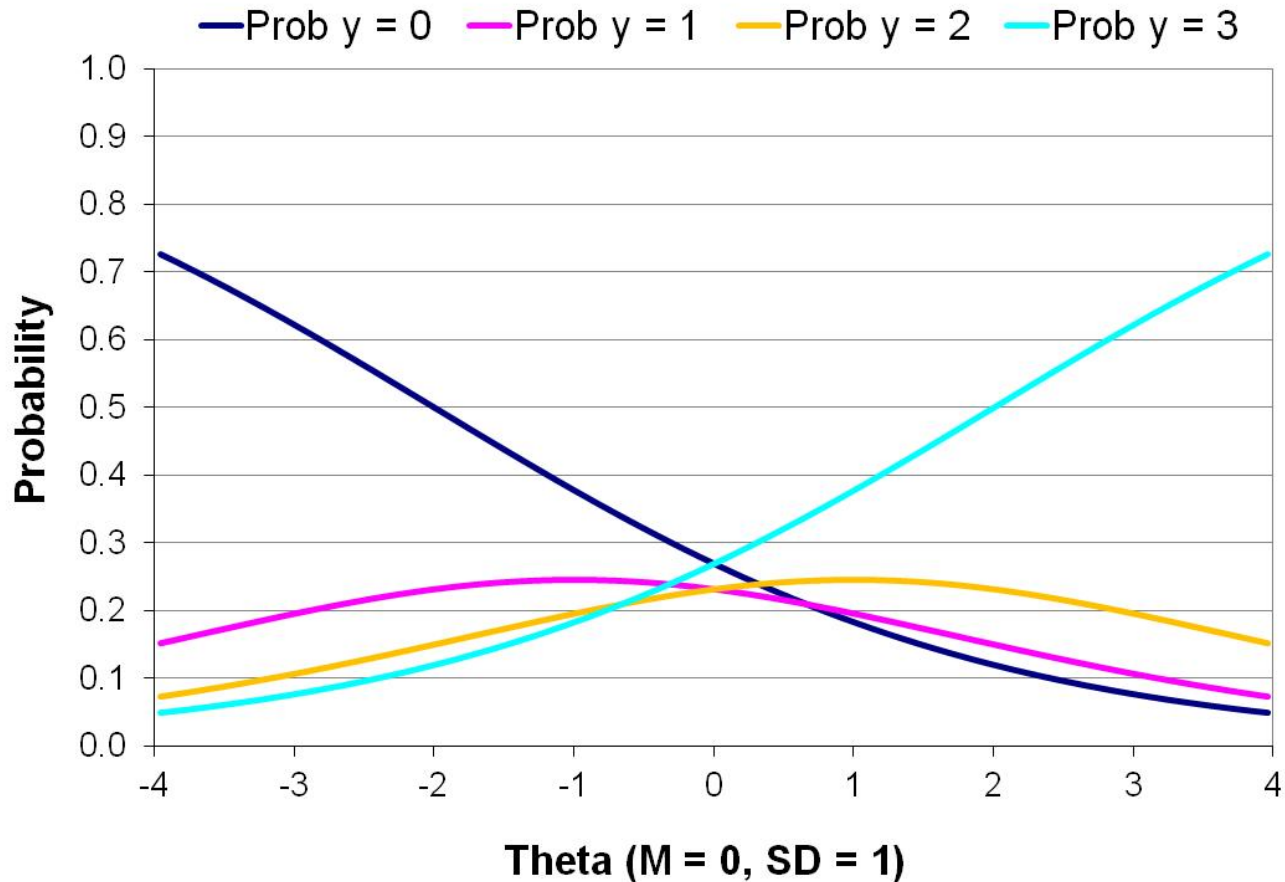


GRM indirectly predicts the probability of each category response across Theta:

$$\begin{aligned}p(y_{is} = 0) &= 1 - p_1 \\p(y_{is} = 1) &= p_1 - p_2 \\p(y_{is} = 2) &= p_2 - p_3 \\p(y_{is} = 3) &= p_3 - 0\end{aligned}$$

Mplus will make this type of Plot for you.

# Category Response Curves: GRM for 4-Category (0|23) Item, $a_i = .5$

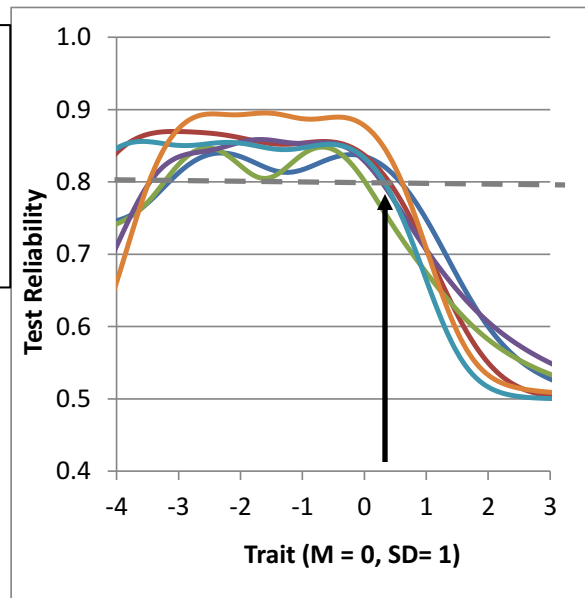
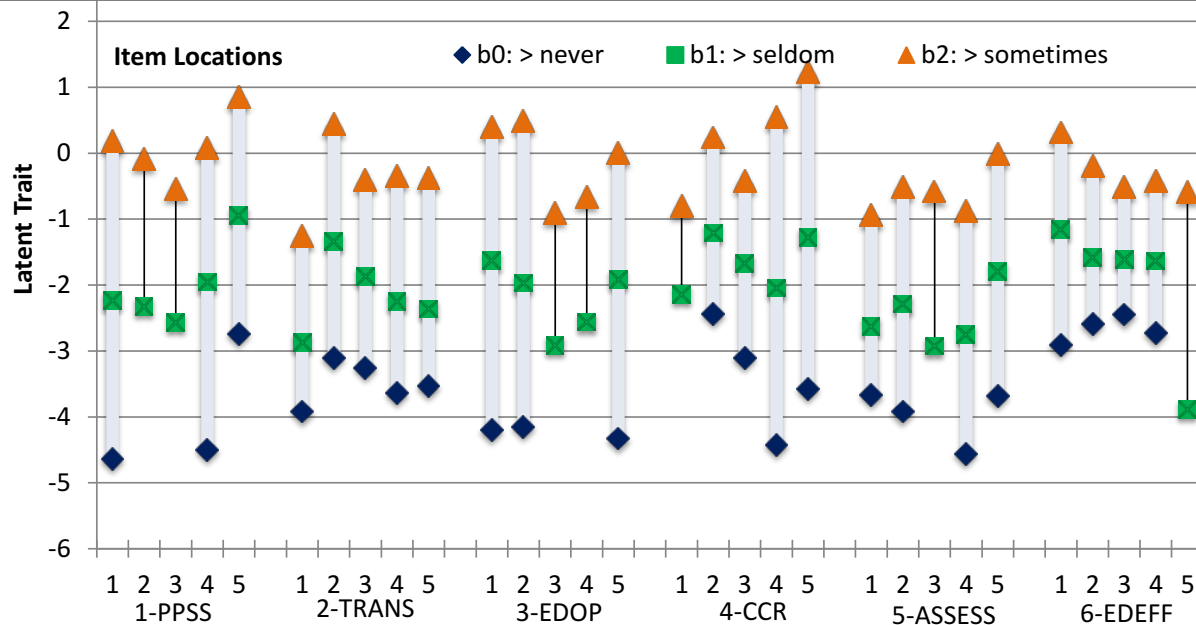
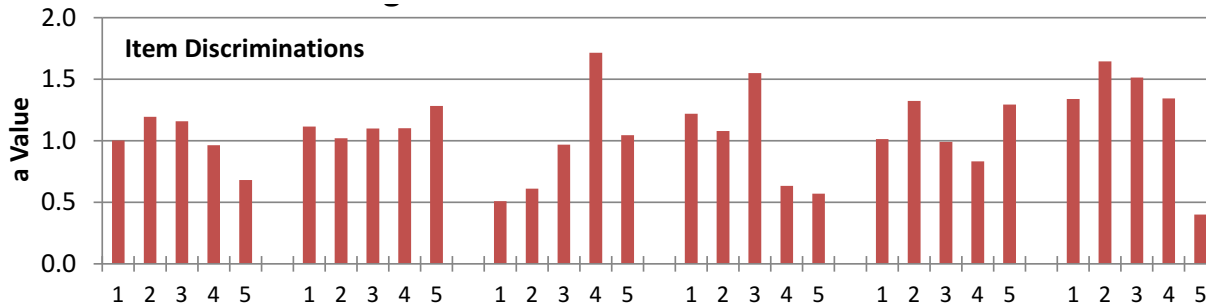


This is exactly what you do NOT want to see.

Although they are ordered, the middle categories are worthless (not differentiated).

Top Panel: Red bars display item discriminations.

Bottom Panel: Item locations for 4 response options:  
*Never, Seldom, Sometimes, and Often*



The location of  $y > \textit{sometimes}$  ranges from  $\sim 0$  to  $.5$  across items, creating lower reliability for traits  $> .5$

Being able to select a higher option (e.g., *almost always*) would improve reliability for high-trait respondents.

# “Modified” (“Rating Scale”) Graded Response Model (MGRM)

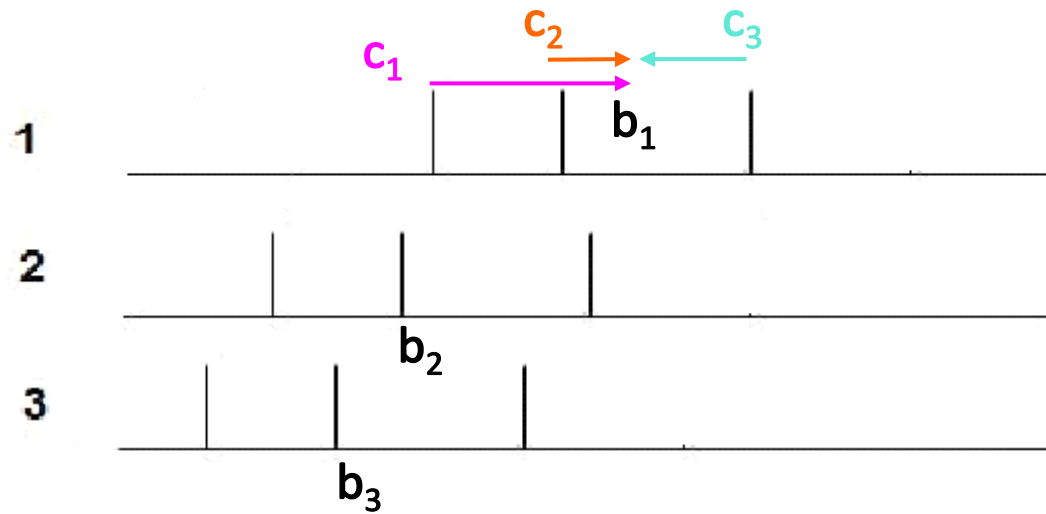
- More parsimonious version of GRM for items with **same response options**
- In GRM,  $k \times \# \text{items}$  difficulties + 1 discrimination are estimated per item
- In MGRM, each item gets own slope and own overall ‘location’ parameter, but the differences between categories around that location are constrained to be equal across items (get a “c” shift for each threshold)
  - So, different  $a_i$  and  $b_i$  per item, but same  $c_1$ ,  $c_2$ , and  $c_3$  across items (**one c = 0**)
  - Not directly available within Mplus, but can be done using threshold constraints

- **0** vs. **1,2,3**:  $\text{Logit}(y_{is} > 0) = a_i(\theta_s - b_i + c_1) \rightarrow p1(y_{is} > 0) = \frac{\exp(a_i(\theta_s - b_i + c_1))}{1 + \exp(a_i(\theta_s - b_i + c_1))}$

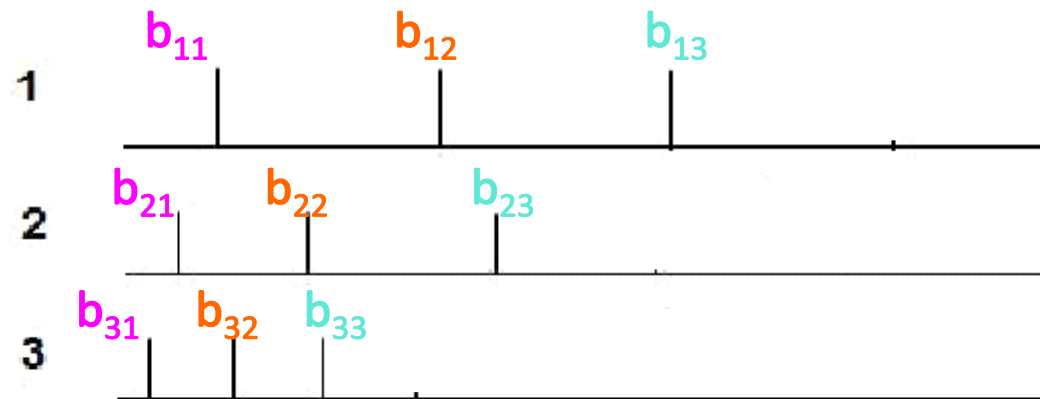
- **0,1** vs. **2,3**:  $\text{Logit}(y_{is} > 1) = a_i(\theta_s - b_i + c_2) \rightarrow p2(y_{is} > 1) = \frac{\exp(a_i(\theta_s - b_i + c_2))}{1 + \exp(a_i(\theta_s - b_i + c_2))}$

- **0,1,2** vs. **3**:  $\text{Logit}(y_{is} > 2) = a_i(\theta_s - b_i + c_3) \rightarrow p3(y_{is} > 2) = \frac{\exp(a_i(\theta_s - b_i + c_3))}{1 + \exp(a_i(\theta_s - b_i + c_3))}$

# Modified vs. Regular GRM



Modified GRM →  
k “shift” c terms: All category distances are same across items, and each item gets its own “ $b_i$ ” overall location



Original GRM →  
k locations per item: All category distances differ across items

Item Difficulty / Latent Ability



# Summary of Models for Ordered Categorical Responses

| Some of these in Mplus via "CATEGORICAL ARE" | Difficulty Per Item Only<br>(category distances equal)          | Difficulty Per Category Per Item              |
|--|---|---|
| Equal discrimination across items (1-PLish)? | (possible, but no special name)                                 | (possible, but no special name)               |
| Unequal discriminations (2-PLish)?           | "Modified GRM" or "Rating Scale GRM"<br>(same response options) | "Graded Response Model"<br>"Cumulative Logit" |

- GRM and Modified GRM are reliable models for ordered categorical data
  - Commonly used in real-world testing; most stable to use in practice
  - Least data demand because all data get used in estimating each  $b_{ki}$
  - Only *major* deviations from the model will end up causing problems

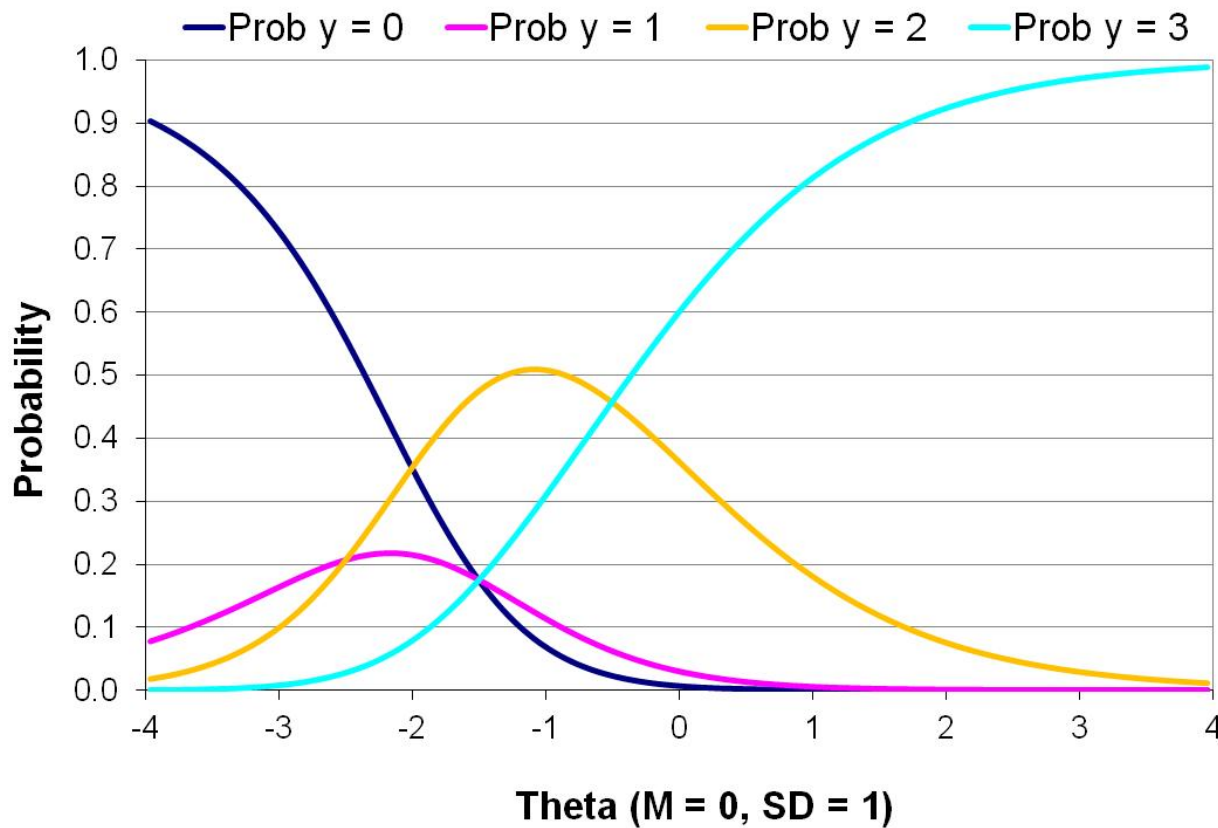
# (Generalized) Partial Credit Model (PCM)

- When you want to **test** an assumption of an ordered underlying continuum
- **# response options doesn't have to be same across items**, but there is no guarantee that every category will be most likely at some point
- Is a “direct, divide-by-total” model (prob of each category is given directly)
- Estimate  $k$  difficulty-like  $\delta_{ki}$  “**step**” parameters, which are the Theta values at which the next category becomes **more likely** (not necessarily 50%)
- Models the probability of **adjacent categories** (“adjacent category logit”)
  - Divide item into a series of binary items, but without order constraints beyond adjacent categories because it only uses those 2 categories ( $c = 0,1,2,3$ ):

IRT for PCM (now in Mplus): Is “generalized” if  $a_i$  is used instead of  $a$

- **If 0 or 1**:  $\text{Logit}(y_{is} = 1) = a_i(\theta_s - \delta_{1i}) \rightarrow p1(y_{is} = 1) = \frac{\exp(a_i(\theta_s - \delta_{1i}))}{1 + \exp(a_i(\theta_s - \delta_{1i}))}$
- **If 1 or 2**:  $\text{Logit}(y_{is} = 2) = a_i(\theta_s - \delta_{2i}) \rightarrow p2(y_{is} = 2) = \frac{\exp(a_i(\theta_s - \delta_{2i}))}{1 + \exp(a_i(\theta_s - \delta_{2i}))}$
- **If 2 or 3**:  $\text{Logit}(y_{is} = 3) = a_i(\theta_s - \delta_{3i}) \rightarrow p3(y_{is} = 3) = \frac{\exp(a_i(\theta_s - \delta_{3i}))}{1 + \exp(a_i(\theta_s - \delta_{3i}))}$

# Category Response Curves: PCM for 4-Category (0 | 23) Item, $a_i=1$



PCM directly predicts the probability of each category response across Theta:

$$p(y_{is} = 0) = 1 - p_1$$

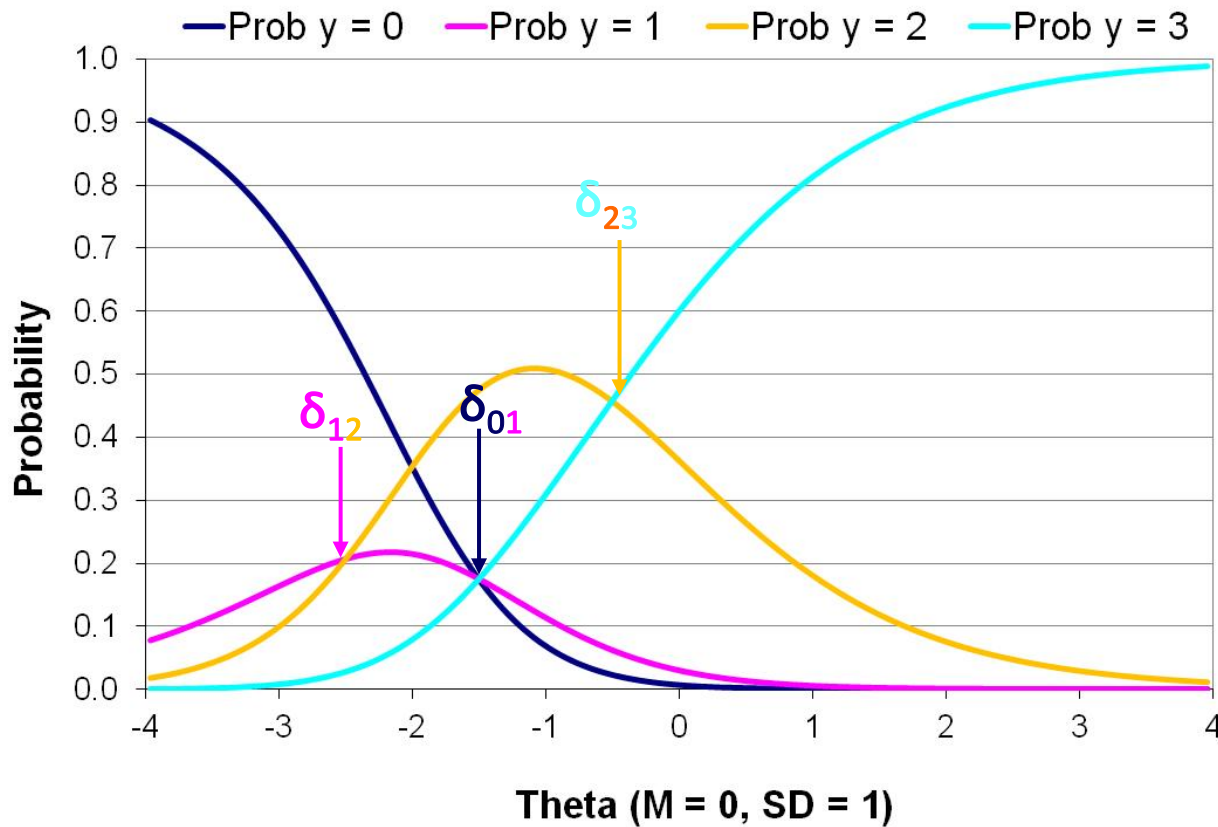
$$p(y_{is} = 1) = p_1$$

$$p(y_{is} = 2) = p_2$$

$$p(y_{is} = 3) = p_3$$

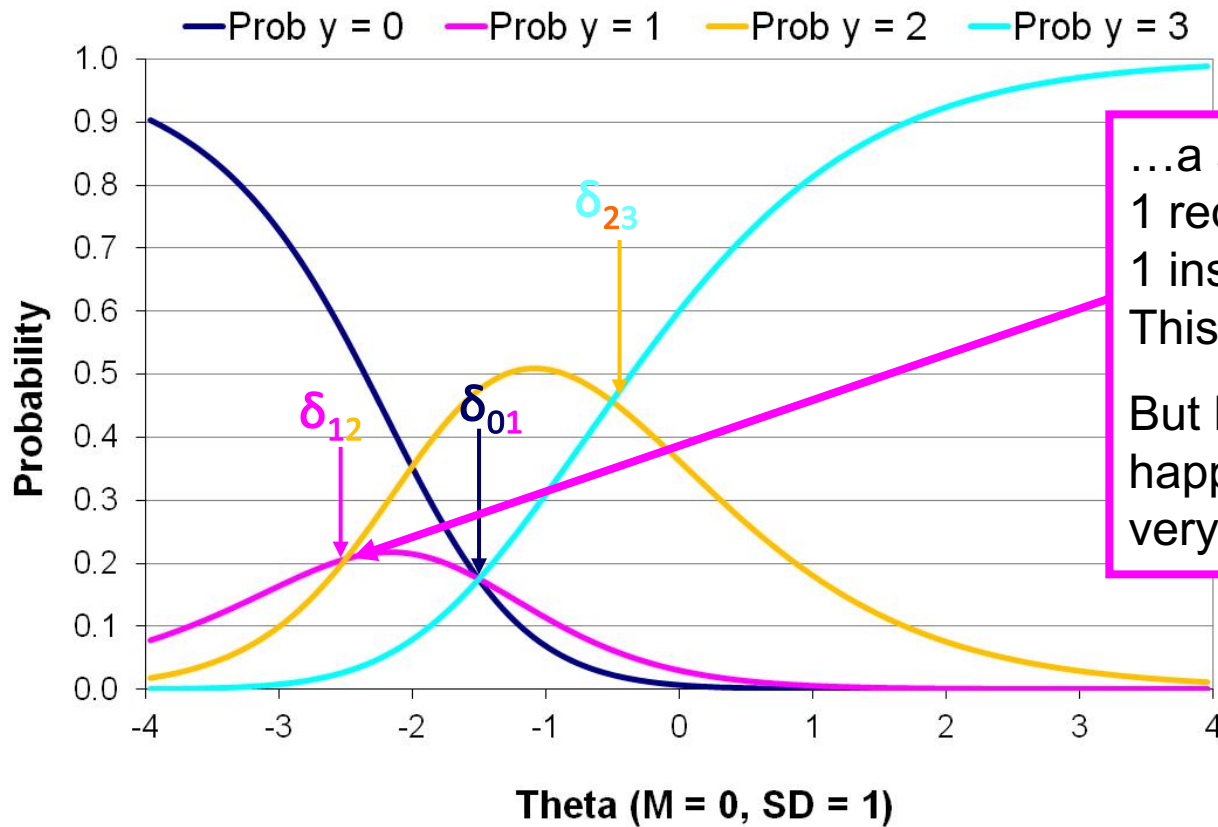
These curves look similar to the GRM, but the location parameters are interpreted differently because they are NOT cumulative, they are only adjacent...

# Category Response Curves: PCM for 4-Category (0|23) Item, $a_i=1$

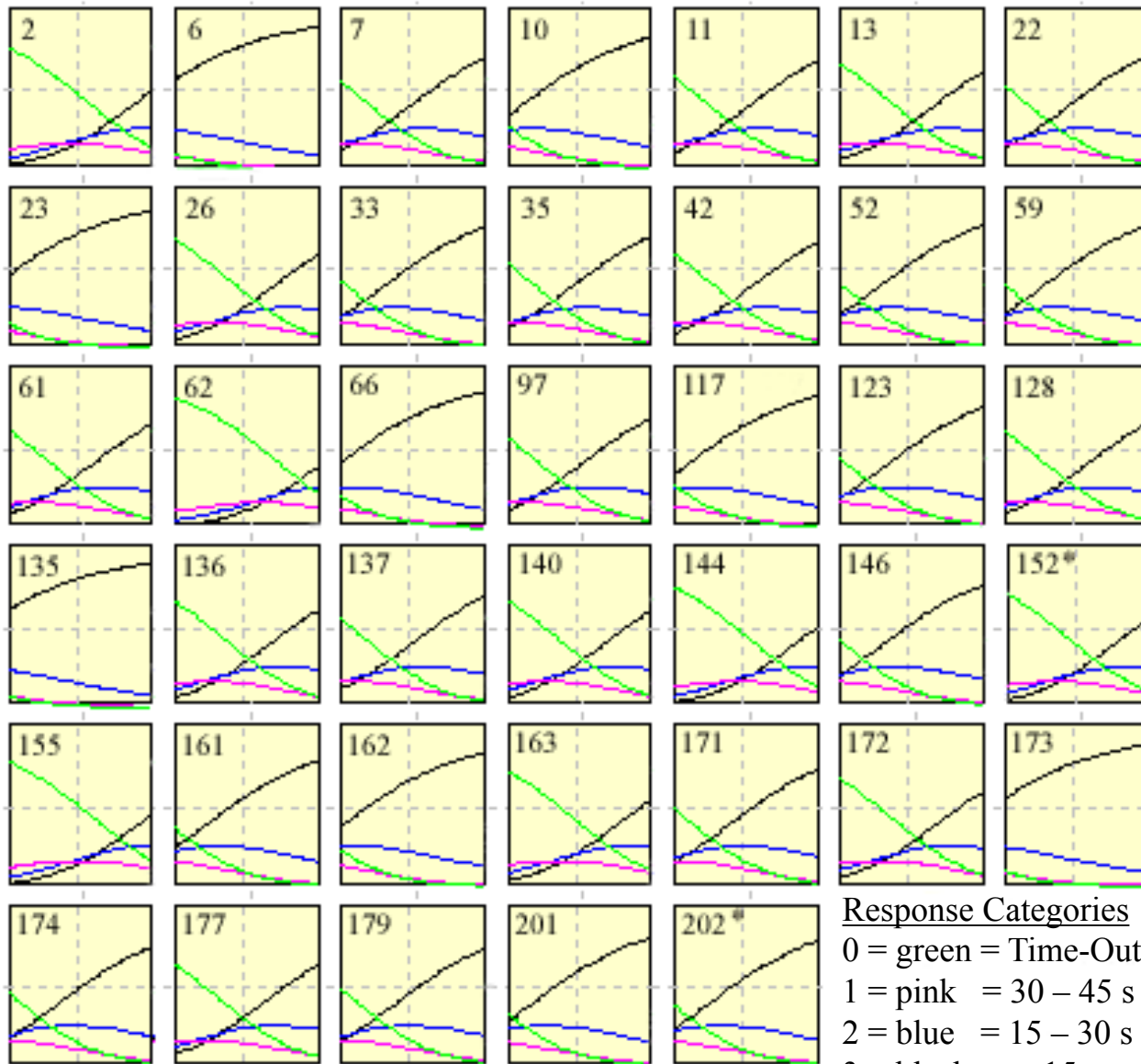


The  $\delta_{ki}$  terms are the location where the next category response becomes more likely (not necessarily 50%).

# Category Response Curves: PCM for 4-Category (0|23) Item, $a_i=1$



...a score of 2 instead of 1 requires less Theta than 1 instead of 0 ...  
This is called a 'reversal'  
But here, this likely only happens because of a very low frequency of 1's

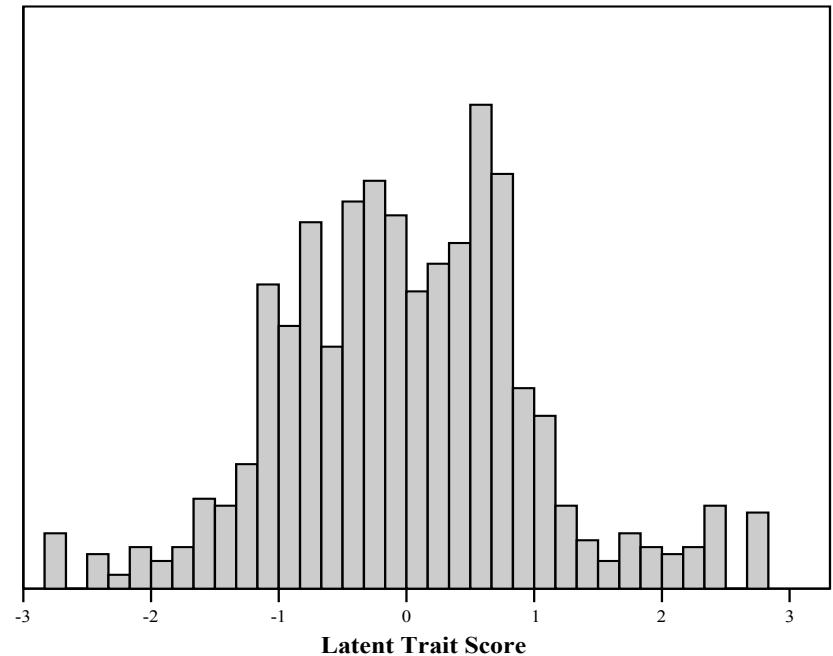
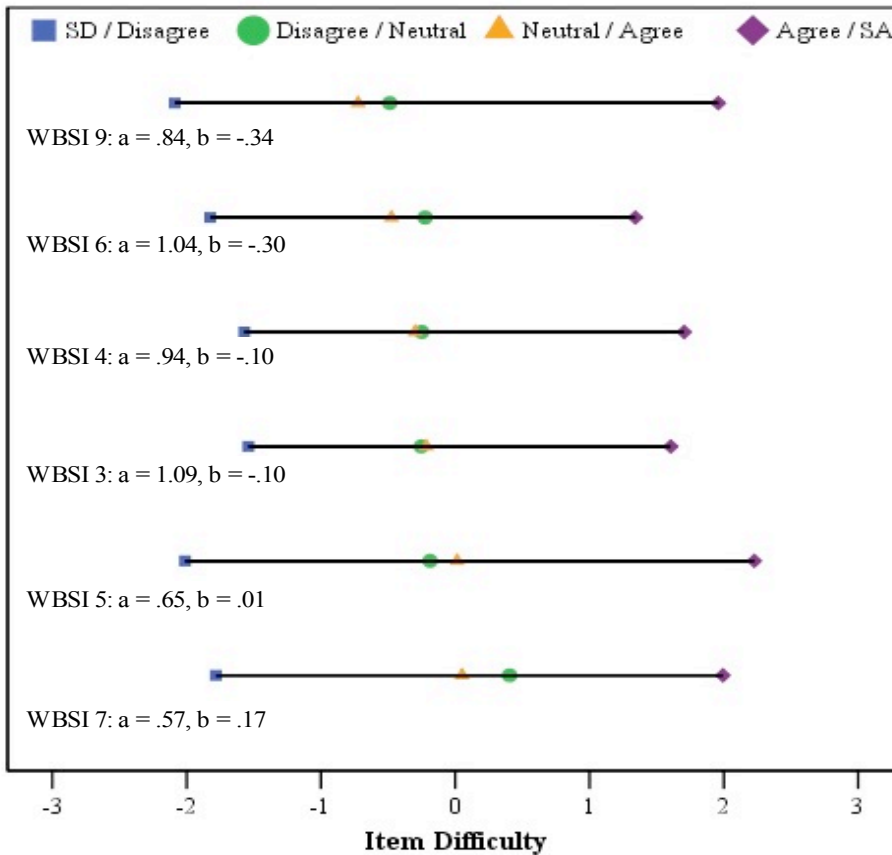


More of what you don't want to see... category response curves from a PCM where reversals are a plenty...

...and the middle categories are fairly useless.

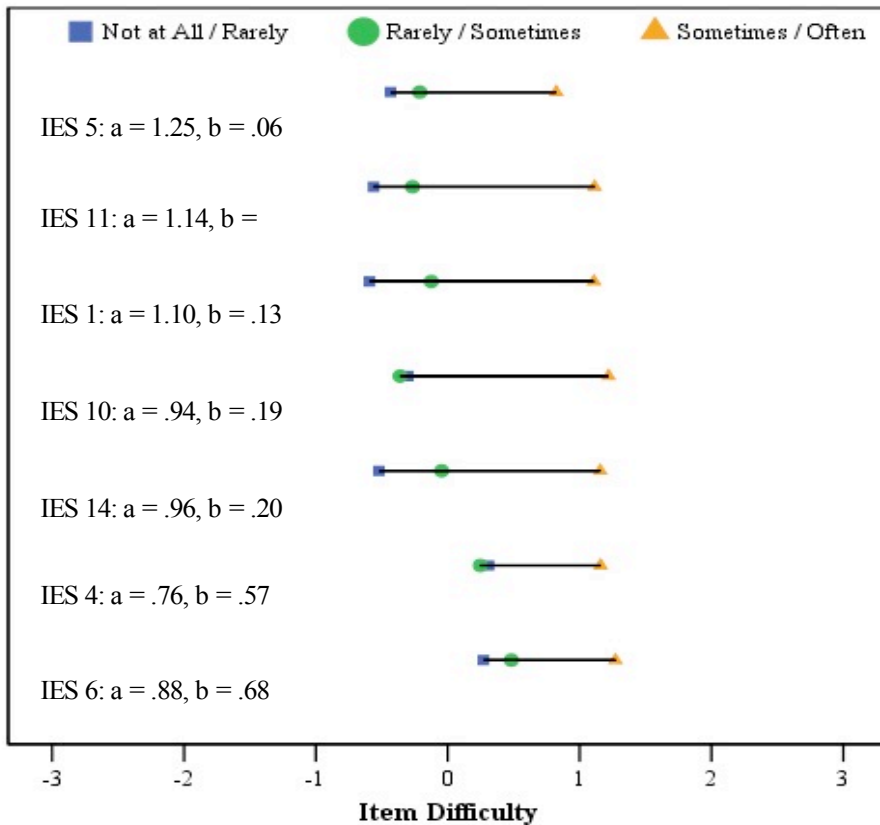
Response Categories  
 0 = green = Time-Out  
 1 = pink = 30 – 45 s  
 2 = blue = 15 – 30 s  
 3 = black = < 15 s  
 \*Misfit ( $p < .05$ )

# PCM Example: General Intrusive Thoughts (5 options)



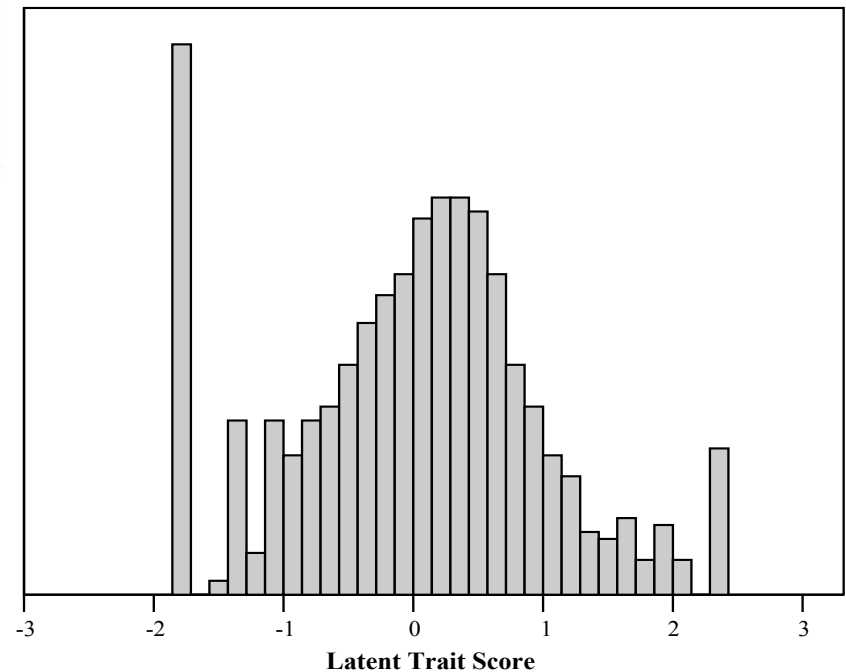
Note that the 4 thresholds **cover a wide range** of the latent trait, and what the distribution of Theta looks like as a result...

But the middle 3 categories are used infrequently and/or are not differentiable



Note that the 3 thresholds **do not cover a wide range** of the latent trait, and what the distribution of theta looks like as a result...

## Partial Credit Model Example: Event-Specific Intrusive Thoughts (4 options)

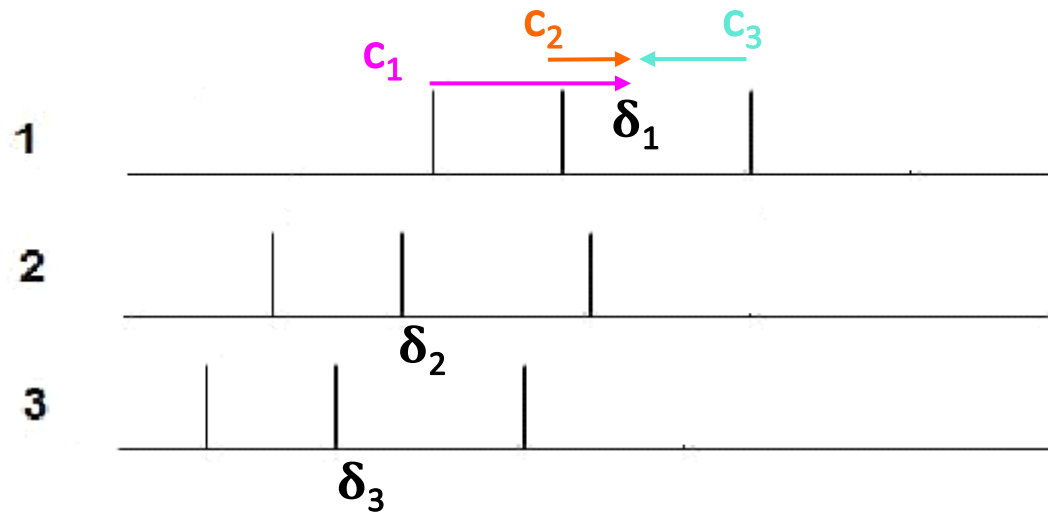




# Rating Scale Model (RSM)

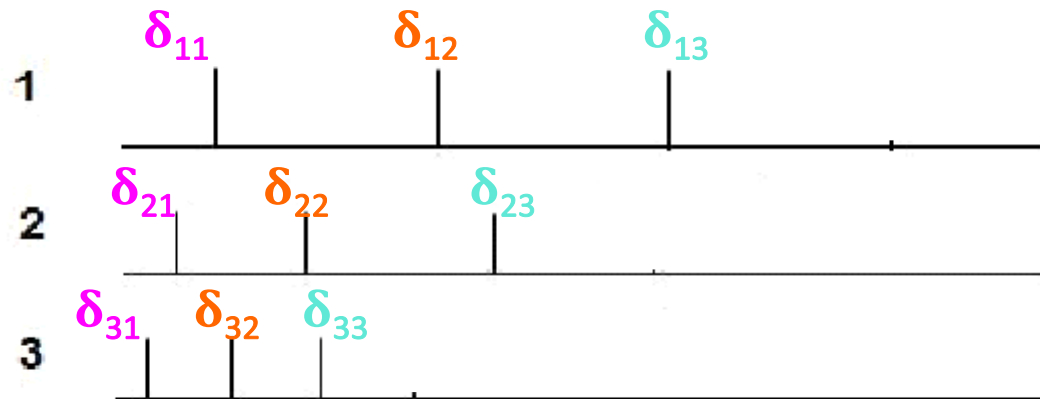
- More parsimonious version of PCM for items with **same response format**
- In PCM,  $k \times \text{\#items}$  step parameters +1 discrimination are estimated per item
- In RSM, each item gets own slope and own overall 'location' parameter, but the differences between categories around that location are constrained to be equal across items (get a "c" shift for each threshold; **one c = 0**)
  - So, different  $b_i$  (and possibly  $a_i$ ) per item, but same  $c_1$ ,  $c_2$ , and  $c_3$  across items
  - Also not available within Mplus
- **If 0 or 1:**  $\text{Logit}(y_{is} = 1) = a(\theta_s - \delta_i + c_1) \rightarrow p1(y_{is} = 1) = \frac{\exp(a(\theta_s - \delta_i + c_1))}{1 + \exp(a(\theta_s - \delta_i + c_1))}$
- **If 1 or 2:**  $\text{Logit}(y_{is} = 2) = a(\theta_s - \delta_i + c_1) \rightarrow p2(y_{is} = 2) = \frac{\exp(a(\theta_s - \delta_i + c_2))}{1 + \exp(a(\theta_s - \delta_i + c_2))}$
- **If 2 or 3:**  $\text{Logit}(y_{is} = 3) = a(\theta_s - \delta_i + c_1) \rightarrow p3(y_{is} = 3) = \frac{\exp(a(\theta_s - \delta_i + c_3))}{1 + \exp(a(\theta_s - \delta_i + c_3))}$

# Rating Scale vs. Regular PCM



Rating Scale →

$k$  “shift”  $c$  terms: All category distances are same across items, and each item gets its own “ $\delta_i$ ” overall location



Original PCM →

$k$  locations per item: All category distances differ across items

Item Difficulty / Latent Ability

# Summary of Models for Maybe-Ordered Categorical Responses

| Not directly available in Mplus              | Difficulty Per Item Only<br>(category distances equal)      | Difficulty Per Category Per Item               |
|--|---|--|
| Equal discrimination across items (1-PLish)? | “Rating Scale PCM”  | “Partial Credit Model”                         |
| Unequal discriminations (2-PLish)?           | “Generalized Rating Scale PCM”??<br>(same response options) | “Generalized PCM”<br>“Adjacent Category Logit” |

- Partial Credit Models test the assumption of ordered categories
  - This can be useful for item screening, but perhaps not for actual analysis
- These models have additional data demands relative to GRM
  - Only data from that threshold get used (i.e., for 1 vs. 2, 0 and 3 don't contribute)
  - So larger sample sizes are needed to identify all model parameters
  - Sometimes categories have to be consolidated to get the model to not blow up

# Nominal Response Model for Unordered Categories

- Ideal for items with no ordering of any kind (e.g., favorite color)
- **# response options don't have to be the same across items**
- NRM is a “direct” model → prob of each category given directly
- Estimate  $k$   $a_i$  per item and  $k$  “intercepts” per item
- Models the probability of **each** category relative to a baseline category (sort of like dummy-coding the outcome variable, here baseline = 0):

0 vs. 1  
Submodel<sub>1</sub>

0 vs. 2  
Submodel<sub>2</sub>

0 vs. 3  
Submodel<sub>3</sub>

Mplus will refer to these “intercepts” using #1, #2, #3 after the item name

- Available in Mplus with NOMINAL ARE option (estimated as an IFA model)
- Can be useful to examine utility of distractors in multiple choice tests

# Example Nominal Response Model (NRM)

IRT version of the NRM: Note that  $a_i$  is NOT the same across submodels...

- If 0 or 1:  $\text{Logit}(y_{is} = 1) = a_{1i}(\theta_s - b_{1i}) \rightarrow p1(y_{is} = 1) = \frac{\exp(a_{1i}(\theta_s + b_{1i}))}{1 + \exp(a_{1i}(\theta_s + b_{1i}))}$
- If 0 or 2:  $\text{Logit}(y_{is} = 2) = a_{2i}(\theta_s - b_{2i}) \rightarrow p2(y_{is} = 2) = \frac{\exp(a_{2i}(\theta_s + b_{2i}))}{1 + \exp(a_{2i}(\theta_s + b_{2i}))}$
- If 0 or 3:  $\text{Logit}(y_{is} = 3) = a_{3i}(\theta_s - b_{3i}) \rightarrow p3(y_{is} = 3) = \frac{\exp(a_{3i}(\theta_s + b_{3i}))}{1 + \exp(a_{3i}(\theta_s + b_{3i}))}$

IFA version of the NRM—what is actually estimated in Mplus:

- If 0 or 1:  $\text{Logit}(y_{is} = 1) = -\tau_{1i} + \lambda_{1i}F_s \rightarrow p1(y_{is} = 1) = \frac{\exp(\mu_{1i} + \lambda_{1i}F_s)}{1 + \exp(\mu_{1i} + \lambda_{1i}F_s)}$
- If 0 or 2:  $\text{Logit}(y_{is} = 2) = -\tau_{2i} + \lambda_{2i}F_s \rightarrow p2(y_{is} = 2) = \frac{\exp(\mu_{2i} + \lambda_{2i}F_s)}{1 + \exp(\mu_{2i} + \lambda_{2i}F_s)}$
- If 0 or 3:  $\text{Logit}(y_{is} = 3) = -\tau_{3i} + \lambda_{3i}F_s \rightarrow p3(y_{is} = 3) = \frac{\exp(\mu_{3i} + \lambda_{3i}F_s)}{1 + \exp(\mu_{3i} + \lambda_{3i}F_s)}$

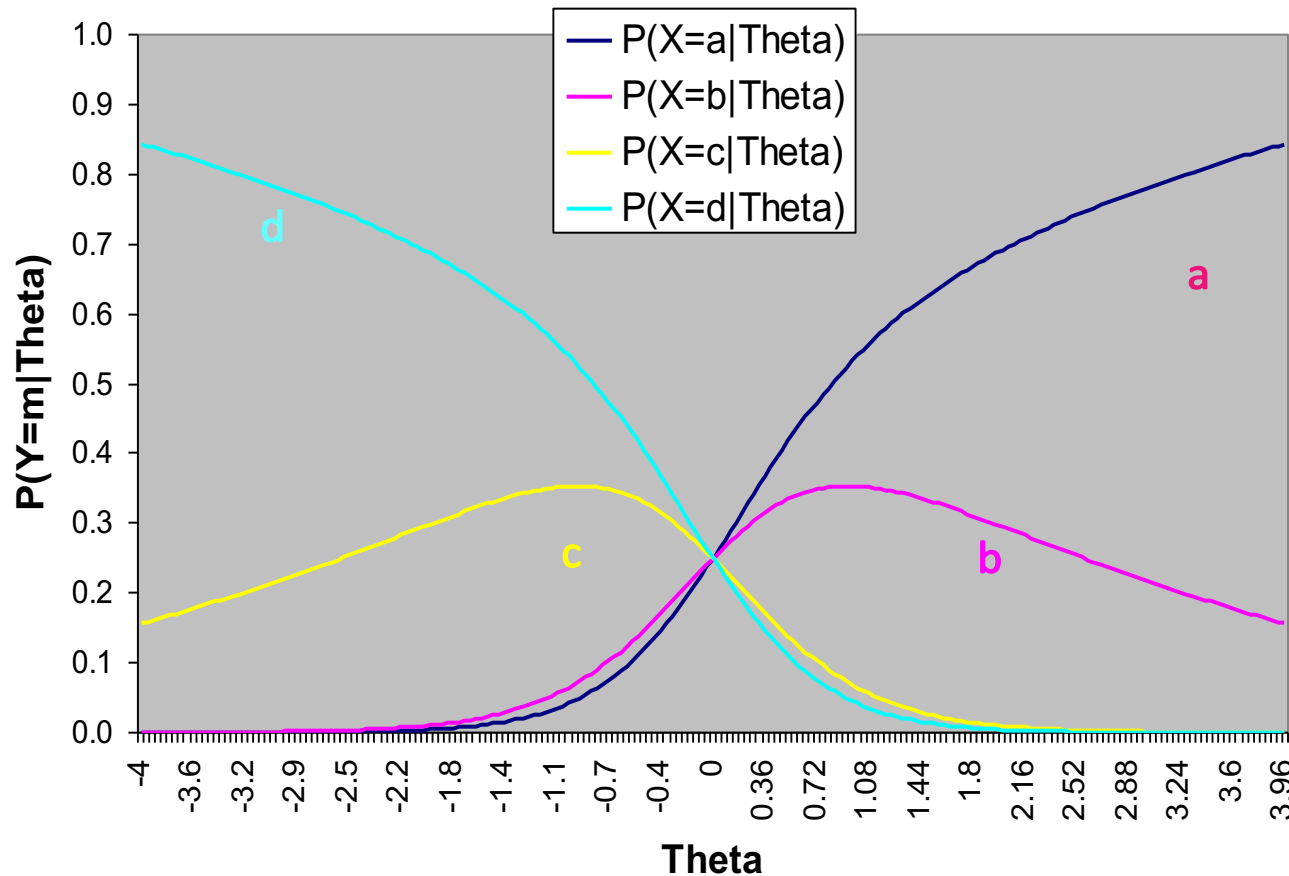
NRM directly predicts probability of each category

- $p(y_{is} = 0) = 1 - p1 + p2 + p3$
- $p(y_{is} = 1) = p1$
- $p(y_{is} = 2) = p2$
- $p(y_{is} = 3) = p3$

IRT  $b_{ki}$  = trait level needed for a 50% prob (logit = 0) of the **lower binary category**  
IFA  $\mu_{ki}$  = logit of the probability of the **higher binary category** when Factor = 0

# Category Response Curves (NRM for 5-Category Item)

Nominal Response Item Response Function



Example Analysis of Multiple Choice Distractors:

People low in Theta are most likely to pick d, but c is their second choice

People high in Theta are most likely to pick a, but b is their second choice

# Summary: Polytomous Models

## Many kinds of polytomous IRT/IFA models...

- Some **assume order** of response options...
  - **Graded Response Model Family** → “cumulative logit model”
    - Model cumulative change in categories using all data for each
- Some allow you to **test order** of response options...
  - **Partial Credit Model Family** → “adjacent category logit model”
    - Model adjacent category thresholds only, so they allow you to see reversals (empirical mis-ordering of your response options with respect to Theta)
    - PCM useful for identifying separability and adequacy of categories
- Some assume **no order** of response options...
  - **Nominal Model** → “baseline category logit model”
    - Useful to examine probability of each response option
    - Is very unparsimonious and thus can be hard to estimate

# Models for Count Outcomes

- Counts: non-negative integer unbounded responses
  - e.g., how many cigarettes did you smoke this week?
  - Traditionally uses natural log link so that predicted outcomes stay  $\geq 0$
- $g(\bullet)$   $\text{Log}(E(y_i)) = \text{Log}(\mu_i) = \text{model} \rightarrow$  predicts mean of  $y_i$
- $g^{-1}(\bullet)$   $E(y_i) = \exp(\text{model}) \rightarrow$  to un-log it, use  $\exp(\text{model})$
- IFA model (no IRT analog):  $\mathbf{Log}(y_{is}) = \boldsymbol{\mu}_i + \boldsymbol{\lambda}_i \mathbf{F}_s + (\mathbf{e}_{is})$ 
  - Model has intercepts and loadings, just predicting  $\log(y_{is})$  instead
  - In Mplus, identify outcomes as COUNT = in VARIABLE: section
- What about an estimated residual variance? It depends...



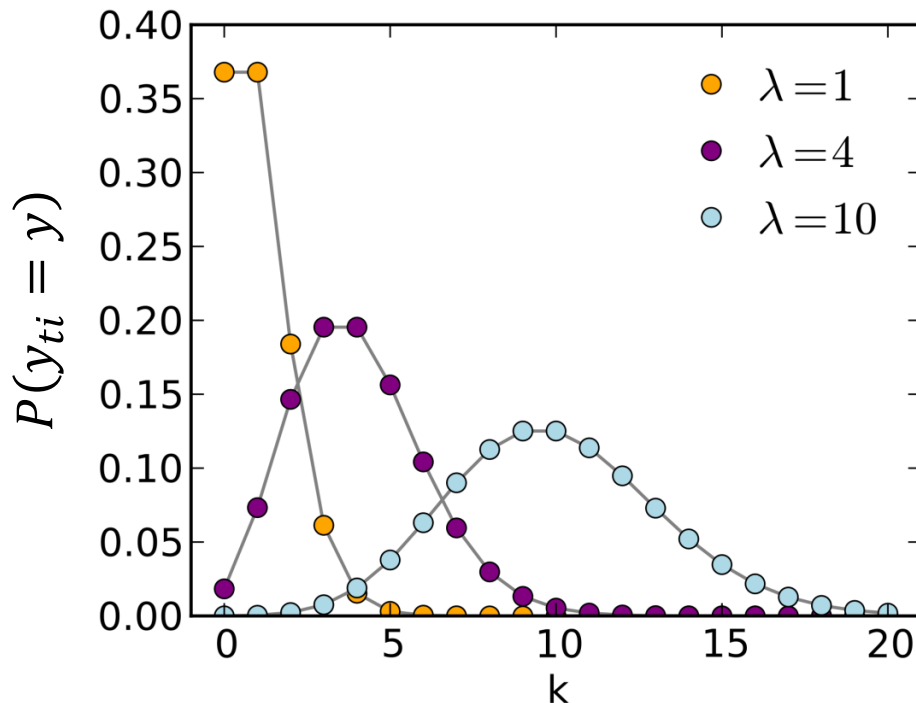
# Poisson Conditional Distribution

- Poisson distribution has one parameter,  $\lambda$ , which is **both its mean and its variance** (so  $\lambda = \text{mean} = \text{variance}$  in Poisson)

- $f(y_i|\lambda) = \text{Prob}(y_i = y) = \frac{\lambda^y * \exp(-\lambda)}{y!}$

- PDF:  $\text{Prob}(y_i = y|\beta_0, \beta_1, \beta_2) = \frac{\mu_i^y * \exp(-\mu_i)}{y!}$

$y!$  is factorial of  $y$



The dots indicate that only integer values are observed.

Distributions with a small expected value (mean or  $\lambda$ ) are predicted to have a lot of 0's.

Once  $\lambda > 6$  or so, the shape of the distribution is close to that of a normal distribution.

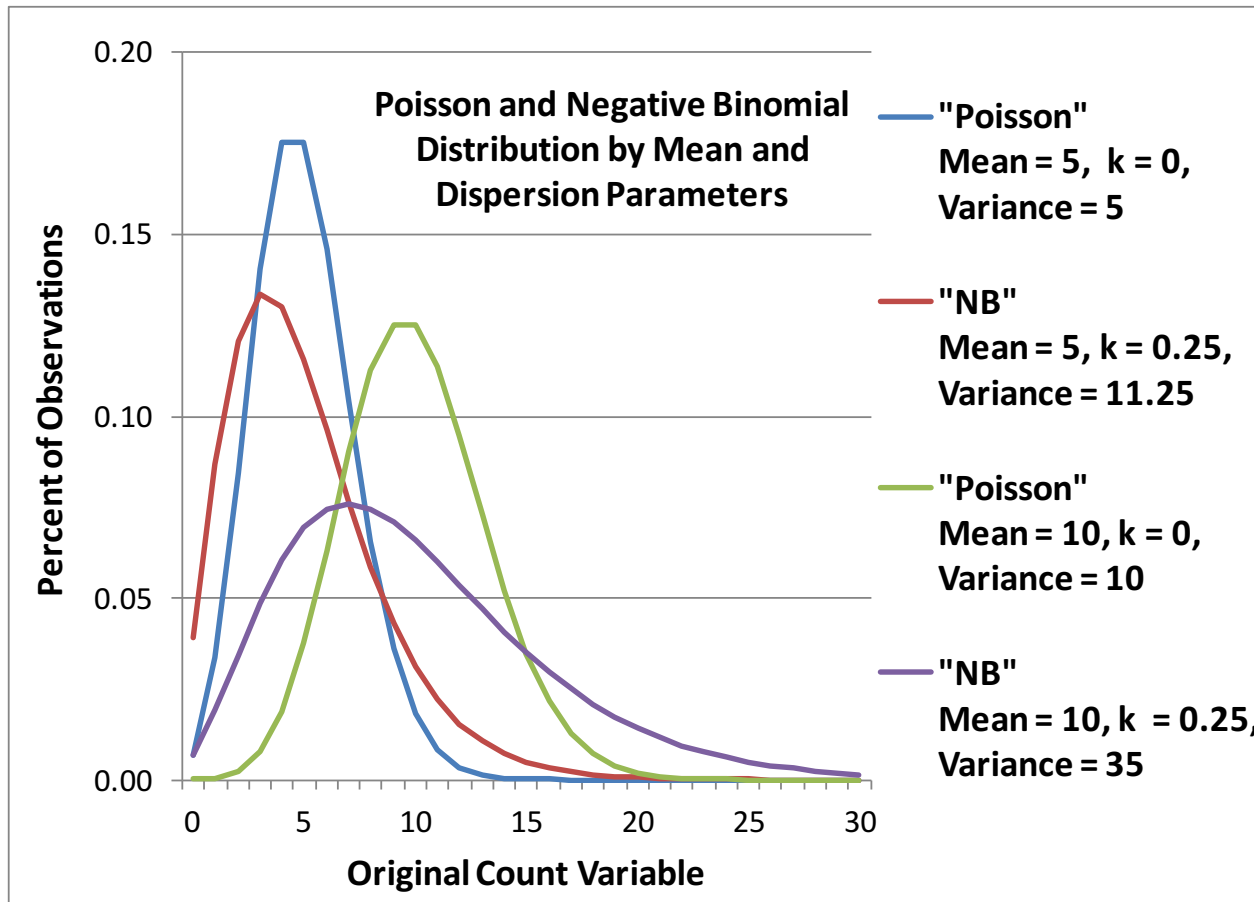
# 3 potential problems for Poisson...

- The standard Poisson distribution is rarely sufficient, though
- **Problem #1: When mean  $\neq$  variance**
  - If variance  $<$  mean, this leads to “under-dispersion” (not that likely)
  - If variance  $>$  mean, this leads to “over-dispersion” (happens frequently)
- **Problem #2: When there are *no* 0 values**
  - Some 0 values are expected from count models, but in some contexts  $y_i > 0$  always (but subtracting 1 won't fix it; need to adjust the model)
- **Problem #3: When there are *too many* 0 values**
  - Some 0 values are expected from the Poisson and Negative Binomial models already, but many times there are even more 0 values observed than that
  - To fix it, there are two main options, depending on what you do to the 0's
- Each of these problems requires a model adjustment to fix it...

# Problem #1: Variance $>$ mean = over-dispersion

- To fix it, we must add a parameter that allows the variance to exceed the mean  $\rightarrow$  a Negative Binomial (NB) distribution
  - Says residuals are a mixture of Poisson and gamma distributions, such that  $\lambda$  itself is a random variable with a gamma distribution
  - So expected mean is still given by  $\lambda$ , but the variance will be  $>$  Poisson
- IFA Model:  $\mathbf{Log}(y_{is}) = \boldsymbol{\mu}_i + \boldsymbol{\lambda}_i \mathbf{F}_s + \mathbf{e}_{is}^G$ 
  - NB has a  $k$  dispersion parameter, such that:  $\text{Var}(y_{is}) = k(1 + k\alpha)$
  - Poisson is nested within negative binomial (can do  $-2\Delta LL$  test of  $\alpha \neq 0$ )
- In Mplus, specify which residual distribution you want:
  - COUNT = y1 (p) y2 (nb);  $\rightarrow$  y1 is Poisson; y2 is negative binomial

# Negative Binomial (NB) = “Stretchy” Poisson...



Mean =  $\lambda$   
Dispersion =  $k$   
 $\text{Var}(y_{is}) = k(1 + k\alpha)$

A Negative Binomial model can be useful for count residuals with extra skewness, but otherwise follow a Poisson distribution.

- Because its  $k$  dispersion parameter is fixed to 0, the Poisson model is nested within the Negative Binomial model—to test improvement in fit:
- Is  $-2(LL_{Poisson} - LL_{NegBin}) > 3.84$  for  $df = 1$ ? Then  $p < .05$ , keep NB

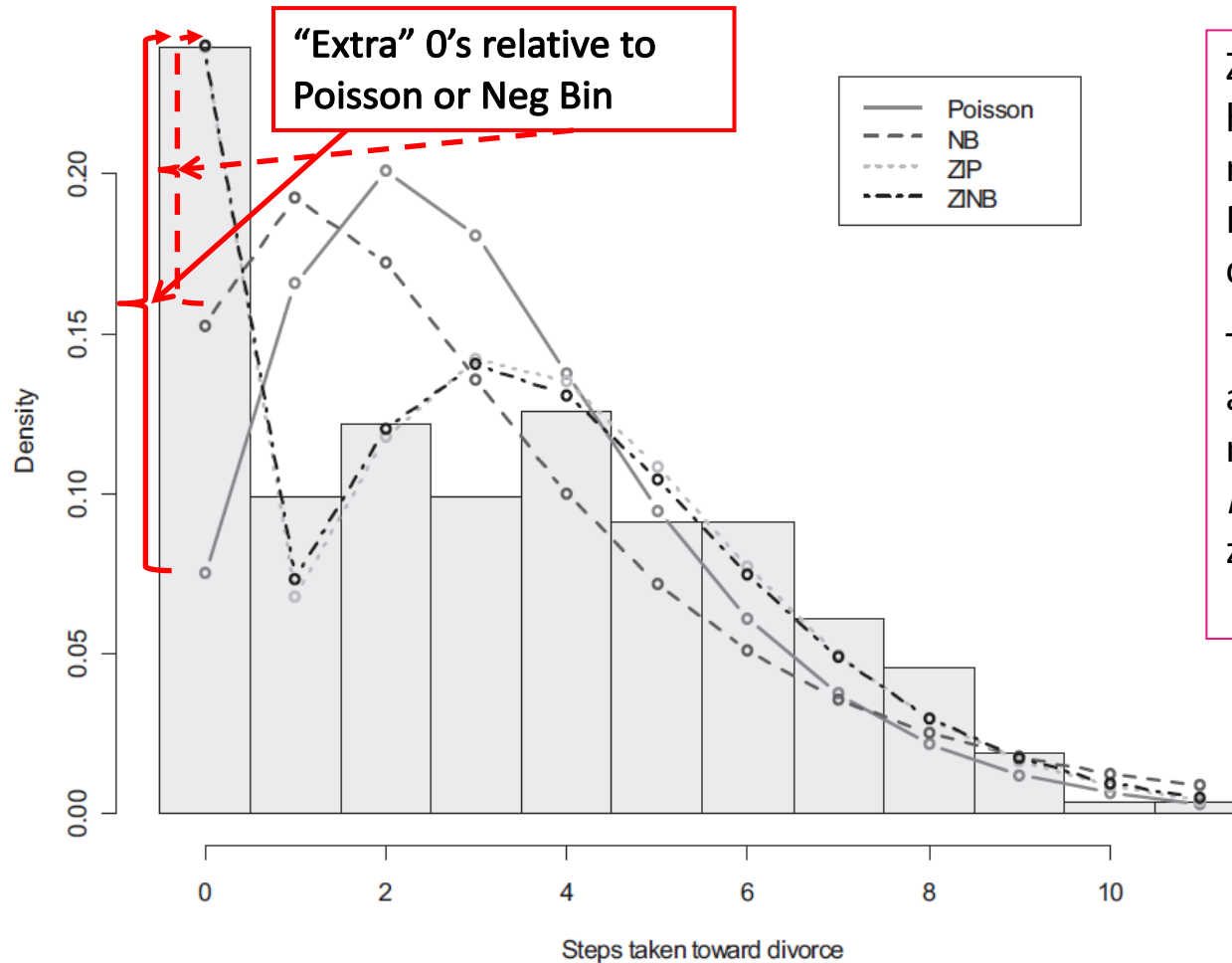
# Problem #2: There are no 0 values

- “Zero-Altered” or “Zero-Truncated” Poisson or Negative Binomial: ZAP/ZANB or ZTP/ZTNB (used in hurdle models)
  - Is usual NB distribution, just not allowing any 0 values
  - In Mplus, COUNT = var1 (nbt); → Negative Binomial Truncated
  - It does NOT work to just subtract 1 and use a usual count distribution
- Poisson PDF was:  $\text{Prob}(y_i = y | \mu_i) = \frac{\mu_i^y * \exp(-\mu_i)}{y!}$
- Zero-Truncated Poisson PDF is:
  - $\text{Prob}(y_i = y | \mu_i, y_i > 0) = \frac{\mu_i^y * \exp(-\mu_i)}{y! [1 - \exp(-\mu_i)]}$
  - $\text{Prob}(y_i = 0) = \exp(-\mu_i)$ , so  $\text{Prob}(y_i > 0) = 1 - \exp(-\mu_i)$
  - Divides by probability of non-0 outcomes so probability still sums to 1

# Problem #3: Too many 0 values, Option #1

- “Zero-Inflated” Poisson ( $\pi$ ) or Negative Binomial ( $nbi$ ); available within Mplus using COUNT =
  - Distinguishes **two kinds of 0 values: expected** and **inflated** (“structural”) through a mixture of distributions (Bernoulli + Poisson/NB)
  - Creates two submodels to predict “if *extra* 0” and “if not, how much”?
    - Does not readily map onto most hypotheses (in my opinion)
    - But a ZIP example would look like this... (ZINB would add  $k$  dispersion, too)
- Submodel 1:  $\text{Logit}(y_{is} = \text{extra } 0) = -\tau_{i1} + \lambda_{i1}F_{s1}$ 
  - Predict being an extra 0 using Link = Logit, Distribution = Bernoulli
  - Don’t have to specify a factor model for this part, can simply allow a threshold that says your data have extra 0 values relative to the usual count distribution
- Submodel 2:  $\text{Log}(y_{is}) = \mu_{i2} + \lambda_{i2}F_{s2}$ 
  - Predict rest of counts (including 0’s expected from count distribution)

# Example of Zero-Inflated Outcomes



Zero-inflated distributions have extra “structural zeros” not expected from Poisson or NB (“stretched Poisson”) distributions.

This can be tricky to estimate and interpret because the model distinguishes between *kinds of zeros* rather than zero or not...

Image borrowed from Atkins & Gallop, 2007

Figure 1. Histogram of Marital Status Inventory with predicted probabilities from regressions. NB = negative binomial; ZIP = zero-inflated Poisson; ZINB = zero-inflated negative binomial.

# Problem #3: Too many 0 values, Option #2

- “Hurdle” models for Poisson or Negative Binomial
  - PH (not in Mplus) or NBH: Explicitly separates 0 from non-0 values through a mixture of distributions (Bernoulli + Zero-Altered Poisson/NB)
  - Creates two submodels to predict “if any 0” and “if not 0, how much”?
    - Easier to think about in terms of prediction (in my opinion)
- Submodel 1:  $\text{Logit}(y_{is} = 0) = -\tau_{i1} + \lambda_{i1}F_{s1}$ 
  - Predict being any 0 using Link = Logit, Distribution = Bernoulli
  - Don't have to specify predictors for this part, can simply allow it to exist
- Submodel 2:  $\text{Log}(y_{is} | y_{is} > 0) = \mu_{i2} + \lambda_{i2}F_{s2}$ 
  - Predict rest of positive counts via Link = Log, Distribution = ZAP/ZANB
- These models are for discrete outcomes, but there is an analogous version for continuous outcomes

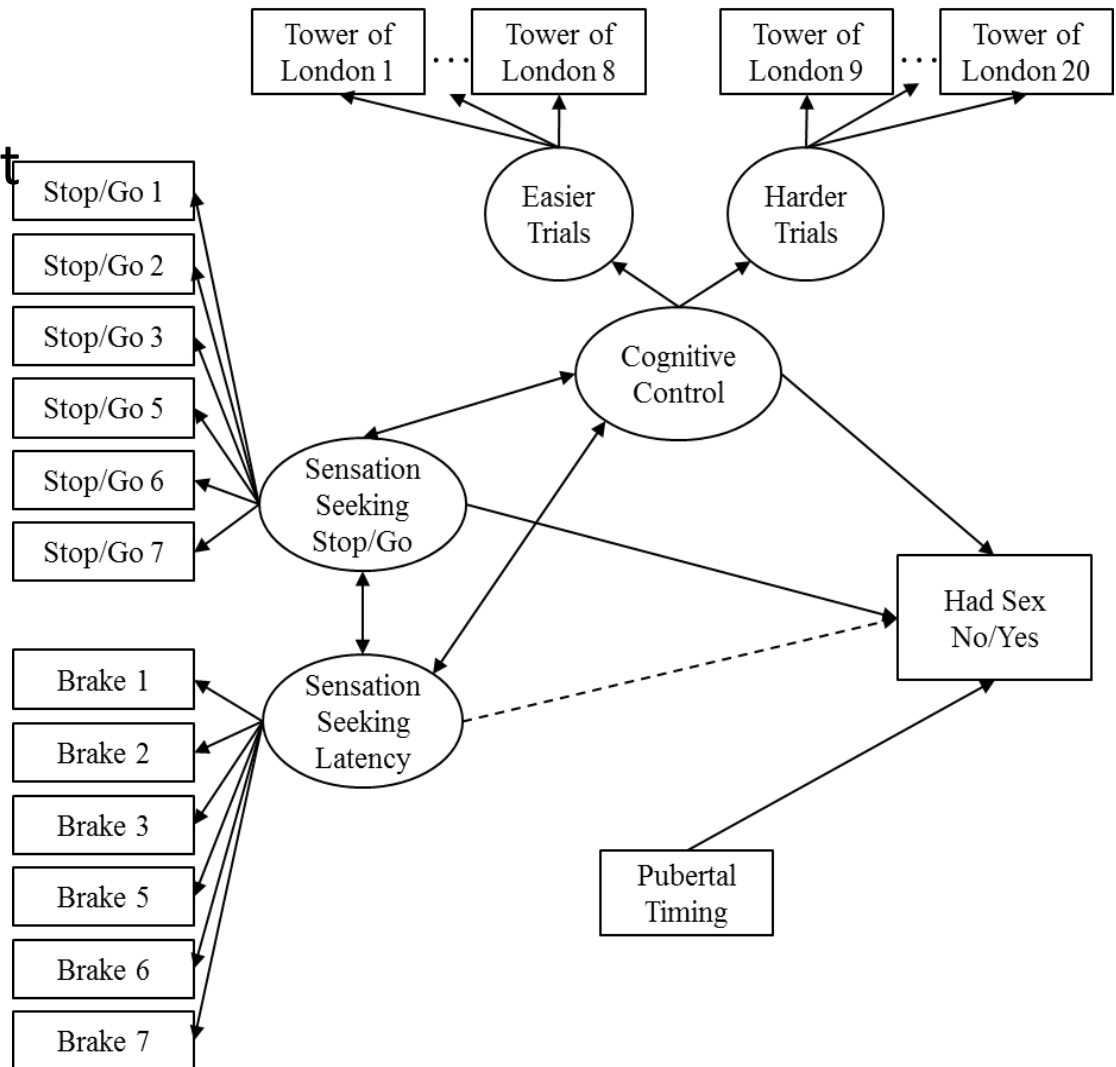


# Two-Part Models for Continuous Outcomes

- A two-part model is an analog to hurdle models for zero-inflated count outcomes (and could be used with count outcomes, too)
  - Explicitly **separates 0 from non-0 values** through a mixture of distributions (Bernoulli + Normal or LogNormal) → usually much easier to explain!
- Submodel 1:  $\text{Logit}(y_i > 0) = -\tau_{i1} + \lambda_{i1}F_{s1} \rightarrow$  predict being NOT 0
- Submodel 2:  $(y_i | y_i > 0) = \mu_{i2} + \lambda_{i2}F_{s2} \rightarrow$  predicts non-0 using normal or lognormal residuals
  - Two-part model uses Mplus DATA TWOPART: command
    - NAMES ARE y1-y4; → list outcomes to be split into 2 parts
    - CUTPOINT IS 0; → where to split observed outcomes
    - BINARY ARE b1-b4; → create names for “0 or not” part
    - CONTINUOUS ARE c1-c4; → create names for “how much” part
    - TRANSFORM IS LOG; → transformation of continuous part
    - 0 or not: predicted by logit of being NOT 0 (“something” is the 1)
    - How much: predicted by transformed normal distribution (like log)

# Two-Part Measurement Model Example

- Two-part model for a sensation-seeking task: 7 driving trials in which light → yellow...
- Two outcomes:
  - Go through light?
  - Latency to brake if not going through?
- Created two latent factors, each of which then predicted other outcomes



# Pile of 0's Taxonomy

- What kind of **amount** do you want to predict?
  - Discrete: Count → Poisson, Stretchy Count → Negative Binomial
  - Continuous: Normal, Log-Normal, Gamma (not in Mplus)
- What kind of **If 0** do you want to predict?
  - Discrete: Extra 0 beyond predicted by amount?  
→ Zero-inflated Poisson or Zero-inflated Negative Binomial
  - Discrete: Any 0 at all?  
→ Hurdle Poisson or Hurdle Negative Binomial
  - Continuous: Any 0 at all?  
→ Two-Part with Continuous Amount (see above)
  - Note: Given the same amount distribution, these alternative ways of predicting 0 will result in the same empty model fit

# Wrapping Up...

- When fitting latent factor models (or when just predicting observed outcomes from observed predictors instead), you have many options to fit non-normal distributions
  - **CFA:** Continuous outcomes with normal residuals,  $X \rightarrow Y$  is linear
    - If residuals may not be normal *but a linear  $X \rightarrow Y$  relationship is still plausible*, you can use MLR estimation instead of ML to control for that
  - **IRT and IFA:** Categorical or ordinal outcomes with Bernoulli/multinomial residuals,  $X \rightarrow$  transformed  $Y$  is linear;  $X \rightarrow$  original  $Y$  is nonlinear
    - Full information MML traditionally paired with IRT version of model; limited information WLSMV traditionally paired with IFA version of model instead
  - **Count family:** Non-negative integer outcomes,  $X \rightarrow \text{Log}(Y)$  is linear
    - Residuals can be Poisson (where mean = variance) or negative binomial (where variance > mean); either can be zero-inflated or zero-truncated
    - Hurdle or two-part may be more direct way to predict/interpret excess zeros (predict zero or not and how much rather than two kinds of zeros)