

Factor analysis

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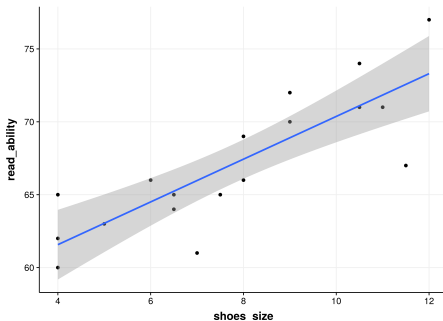
Outline of section

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 - Purpose of factor analysis
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Motivation example (Using a Regression example)

For children in elementrays school

Observed variable: Shoe size and reading ability



Purpose of factor analysis

- Dimension reduction (it is not the most important in factor analysis)
- Describe the covariance relationship among many observable variables in terms of a few underlying, but unobservable (latent) variable.

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The Orthogonal Factor Model

The observable random vector \mathbf{X} , with components has mean μ and covariance matrix Σ . \mathbf{X} is linearly dependent upon a few unobservable random variables F_1, F_2, \dots, F_m called **common factor**, $\varepsilon_1, \varepsilon_2, \dots, \varepsilon_p$ called **specific factors**, L called **specific loading**

$$X_1 - \mu_1 = \ell_{11}F_1 + \ell_{12}F_2 + \dots + \ell_{1m}F_m + \varepsilon_1$$

$$X_2 - \mu_2 = \ell_{21}F_1 + \ell_{22}F_2 + \dots + \ell_{2m}F_m + \varepsilon_2$$

$$\vdots$$

$$X_p - \mu_p = \ell_{p1}F_1 + \ell_{p2}F_2 + \dots + \ell_{pm}F_m + \varepsilon_p$$

in matrix notation

$$\mathbf{X} - \boldsymbol{\mu} = \mathbf{LF} + \boldsymbol{\varepsilon}$$

Assume that

$$E(\mathbf{F}) = \mathbf{0}_{(m \times 1)}, \text{Cov}(\mathbf{F}) = E(\mathbf{FF}') = \mathbf{I}_{(m \times m)}, \text{Cov}(\boldsymbol{\varepsilon}, \mathbf{F}) = \mathbf{0}_{(p \times m)}$$

$$E(\boldsymbol{\varepsilon}) = \mathbf{0}_{(p \times 1)}, \text{Cov}(\boldsymbol{\varepsilon}) = E(\boldsymbol{\varepsilon}\boldsymbol{\varepsilon}') = \boldsymbol{\Psi}_{(p \times p)}$$

where $\boldsymbol{\Psi}$ is a diagonal matrix.

So the covariance structure for \mathbf{X} From this model

$$\begin{aligned}
 \Sigma &= \text{Cov}(\mathbf{X}) = E((\mathbf{X} - \mu)(\mathbf{X} - \mu)') \\
 &= \mathbf{L}E(\mathbf{F}\mathbf{F}')\mathbf{L}' + \cancel{E(\varepsilon\mathbf{F}')\mathbf{L}'} + \cancel{\mathbf{L}E(\mathbf{F}\varepsilon')} + E(\varepsilon\varepsilon') \\
 &= \mathbf{L}\mathbf{L}' + \Psi
 \end{aligned}$$

$$\text{Cov}(\varepsilon, \mathbf{F}) = E(\varepsilon\mathbf{F}') = 0,$$

$$\text{Cov}(\mathbf{X}, \mathbf{F}) = E(\mathbf{X} - \mu\mathbf{F}') = \mathbf{L}E(\mathbf{F}\mathbf{F}') + E(\varepsilon\mathbf{F}') = \mathbf{L}.$$

- Communality h_i^2 : portion of $\text{Var}(X_i)$ contributed by the m common factors.
- Specific variance ψ_i : portion of $\text{Var}(X_i)$ due to specific factor.

$$\underbrace{\sigma_{ii}}_{\text{Var}(X_i)} = \underbrace{\ell_{i1}^2 + \ell_{i2}^2 + \cdots + \ell_{im}^2}_{\text{Communality}} + \underbrace{\psi_i}_{\text{Specific variance}} = h_i^2 + \psi_i$$

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Principal Component

The spectral decomposition of provides is with one factoring of the covariance matrix Σ . Let Σ have eigenvalue-eigenvector pairs (λ_i, e_i) with $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_p \geq 0$. Then

$$\begin{aligned}\Sigma &= \lambda_1 e_1 e_1' + \lambda_2 e_2 e_2' + \dots + \lambda_p e_p e_p' \\ &= \begin{bmatrix} \sqrt{\lambda_1} e_1 & \sqrt{\lambda_2} e_2 & \dots & \sqrt{\lambda_p} e_p \end{bmatrix} \begin{bmatrix} \sqrt{\lambda_1} e_1' \\ \sqrt{\lambda_2} e_2' \\ \vdots \\ \sqrt{\lambda_p} e_p' \end{bmatrix}\end{aligned}$$

The above form is not useful since $m = p$.

Most covariance matrices cannot be factored as \mathbf{LL}' when m is much less than p ;

So allowing for specific factors, we find that the approximation becomes

$$\begin{aligned}\Sigma &\doteq \mathbf{LL}' + \psi \\ &= \begin{bmatrix} \sqrt{\lambda_1}e_1 & \sqrt{\lambda_2}e_2 & \cdots & \sqrt{\lambda_m}e_m \end{bmatrix} \begin{bmatrix} \sqrt{\lambda_1}e'_1 \\ \sqrt{\lambda_2}e'_2 \\ \vdots \\ \sqrt{\lambda_p}e'_m \end{bmatrix} \\ &\quad + \begin{bmatrix} \psi_1 & 0 & \cdots & 0 \\ 0 & \psi_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \psi_p \end{bmatrix}\end{aligned}$$

Use **S** or **R** in place of Σ

How to choose m ?

The m is chosen such that a “suitable proportion” of the total sample variance is explained

$$\left(\begin{array}{c} \text{Proportion of total} \\ \text{sample variance} \\ \text{due to } j\text{th factor} \end{array} \right) = \left\{ \begin{array}{ll} \frac{\hat{\lambda}_j}{s_{11} + s_{22} + \cdots + s_{pp}} & \text{for a factor analysis of } \mathbf{S} \\ \frac{\hat{\lambda}_j}{p} & \text{for a factor analysis of } \mathbf{R} \end{array} \right. \quad (9-20)$$

Estimation by MLE

The common factors \mathbf{F} and specific factors ε are assumed to be normally distributed: $\mathbf{F} \sim \mathcal{N}_m(\mathbf{0}, \mathbf{I}_m)$ and $\varepsilon \sim \mathcal{N}_p(\mathbf{0}, \Psi)$

The maximum likelihood estimates of the communalities are

$$\hat{h}_i^2 = \hat{\ell}_{i1}^2 + \hat{\ell}_{i2}^2 + \cdots + \hat{\ell}_{im}^2 \quad \text{for } i = 1, 2, \dots, p$$

so

$$\left(\begin{array}{c} \text{Proportion of total sample} \\ \text{variance due to } j\text{th factor} \end{array} \right) = \frac{\hat{\ell}_{1j}^2 + \hat{\ell}_{2j}^2 + \cdots + \hat{\ell}_{pj}^2}{s_{11} + s_{22} + \cdots + s_{pp}}$$

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Rotation

- Factor rotation = Orthogonal transformation of the factors
- Different orthogonal transformation lead to the same estimated covariance matrix, residual matrix, specific variances, and communalities

$$\mathbf{L}^* = \mathbf{L}\mathbf{T} \text{ then } \mathbf{L}\mathbf{L}' + \Psi = \mathbf{L}\mathbf{T}\mathbf{T}'\mathbf{L}' + \Psi = \mathbf{L}^*\mathbf{L}^{*'} + \Psi$$

- Different orthogonal transformation lead to different meanings/interpretations of factors
- Select the one with most meaningful interpretation

- Varimax rotation

Kaiser [9] has suggested an analytical measure of simple structure known as the *varimax* (or normal varimax) *criterion*. Define $\tilde{\ell}_{ij}^* = \tilde{\ell}_{ij} / h_i$ to be the rotated coefficients scaled by the square root of the communalities. Then the (normal) varimax procedure selects the orthogonal transformation \mathbf{T} that makes

$$V = \frac{1}{p} \sum_{j=1}^m \left[\sum_{i=1}^p \tilde{\ell}_{ij}^{*4} - \left(\sum_{i=1}^p \tilde{\ell}_{ij}^{*2} \right)^2 / p \right] \quad (9-45)$$

as large as possible.

$$V \propto \sum_{j=1}^m \left(\text{variance of squares of (scaled) loadings for } j\text{th factor} \right) \quad (9-46)$$

$$V = \sum_{j=1}^m \left\{ \frac{1}{p} \sum_{i=1}^p (\tilde{\ell}_{ij}^*)^4 - \left(\frac{1}{p} \sum_{i=1}^p \tilde{\ell}_{ij}^{*2} \right)^2 \right\}$$

* Idea = $L = \begin{bmatrix} \begin{bmatrix} \times \\ \times \\ \times \\ \times \\ \times \end{bmatrix} & \dots & \begin{bmatrix} \times \\ \times \\ \times \\ \times \\ \times \end{bmatrix} \end{bmatrix}_{p \times m} \longrightarrow L^* = \begin{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} & \dots & \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \end{bmatrix}$

variations large



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Factor Score

Q: What is factor Score?

Ans: the estimated values of the common factors. (not real values)

Suppose first that the mean vector μ, \mathbf{L}, Ψ are known for the factor model

Model: $\mathbf{X} - \mu = \mathbf{L} \underbrace{\mathbf{F}}_{\text{Random}} + \varepsilon$

Data: Further, regard the specific factors $\varepsilon = [\varepsilon_1, \varepsilon_2, \dots, \varepsilon_p]$ as errors. Since $\text{Var}(\varepsilon_i) = \Psi_i, i = 1, 2, \dots, p$, need not be equal.

Solve:

- WLSE: $\hat{\mathbf{f}}_j = \mathbf{L}'\Psi^{-1}\mathbf{L}^{-1}\mathbf{L}'\Psi^{-1}(\mathbf{x} - \mu).$
- OLSE: (Principal component) $\hat{\mathbf{f}}_j = \mathbf{L}'\mathbf{L}^{-1}\mathbf{L}'(\mathbf{x} - \mu)$
- Regression: $\hat{\mathbf{f}} = \hat{\mathbf{L}}'\mathbf{S}^{-1}(\mathbf{x}_j - \bar{\mathbf{x}}), j = 1, 2, \dots, n,$
where \mathbf{S} (the original sample covariacne matrix)

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Example (Stock price data)

Table 9.3

Variable	Maximum likelihood			Principal components		
	Estimated factor loadings		Specific variances $\hat{\psi}_i = 1 - \hat{h}_i^2$	Estimated factor loadings		Specific variances $\tilde{\psi}_i = 1 - \tilde{h}_i^2$
	F_1	F_2		F_1	F_2	
1. J P Morgan	.115	.755	.42	.732	-.437	.27
2. Citibank	.322	.788	.27	.831	-.280	.23
3. Wells Fargo	.182	.652	.54	.726	-.374	.33
4. Royal Dutch Shell	1.000	-.000	.00	.605	.694	.15
5. Texaco	.683	-.032	.53	.563	.719	.17
Cumulative proportion of total (standardized) sample variance explained	.323	.647		.487	.769	

Handwritten notes:

- A bracket under the F_1 and F_2 loadings for the first five variables is labeled "not orthogonal".
- A bracket under the F_1 and F_2 loadings for the first five variables is labeled "orthogonal".

Python & R

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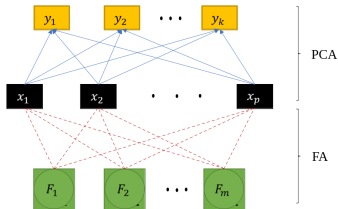
- Mixed data type
R:FAMD - Factor Analysis of Mixed Data
Python factor analysis library (PCA, CA, MCA, MFA, FAMD)

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Conclusion

- Principal component analysis (PCA) is to summarize a set of variables with a few components by using their linear combinations.
- Factor analysis (FA) is to find latent variables behind a set of variables.
- Both methods deal with the covariance structure of variables
 - PCA focuses on the variances
 - FA focuses on the correlations



Thank you for your kind attention.