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BLOCK TESTING IN COVARIANCE AND PRECISION MATRICES FOR FUNCTIONAL DATA ANALYSIS

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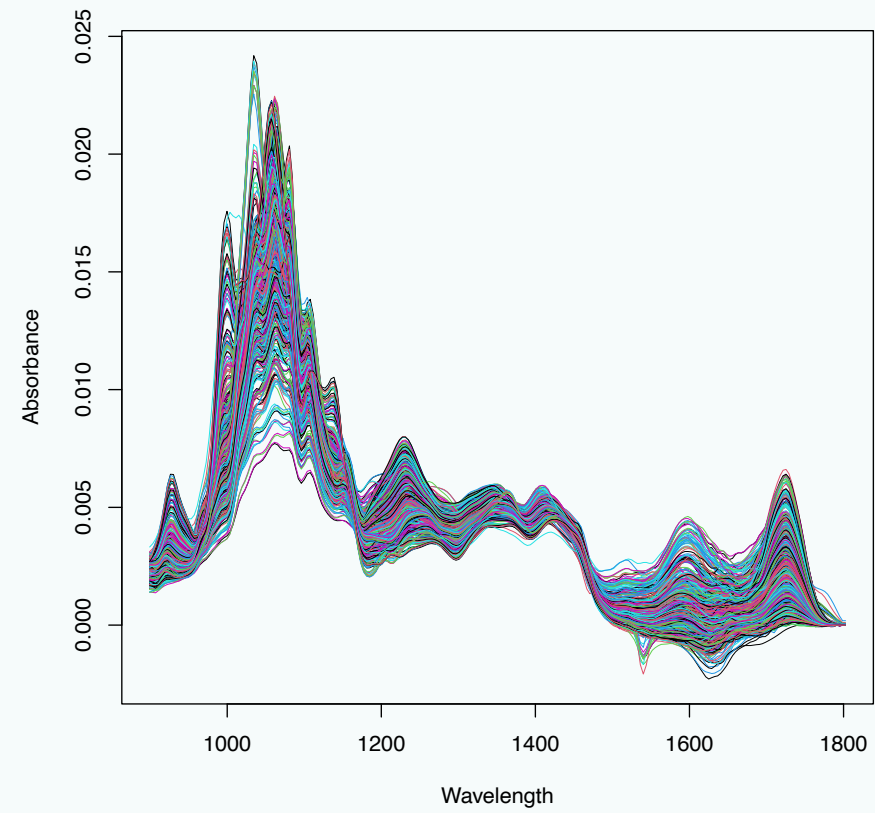
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MOTIVATION

- **Infrared spectroscopy:** a technique used to study the composition of a mixture.
- Data are infrared spectra, which can be seen as continuous functions of the wavelength.
- The different parts of the signal are related to the mixture components.
- We are particularly interested in the dependency structure of data along the domain, to understand if the different components are related between each other.

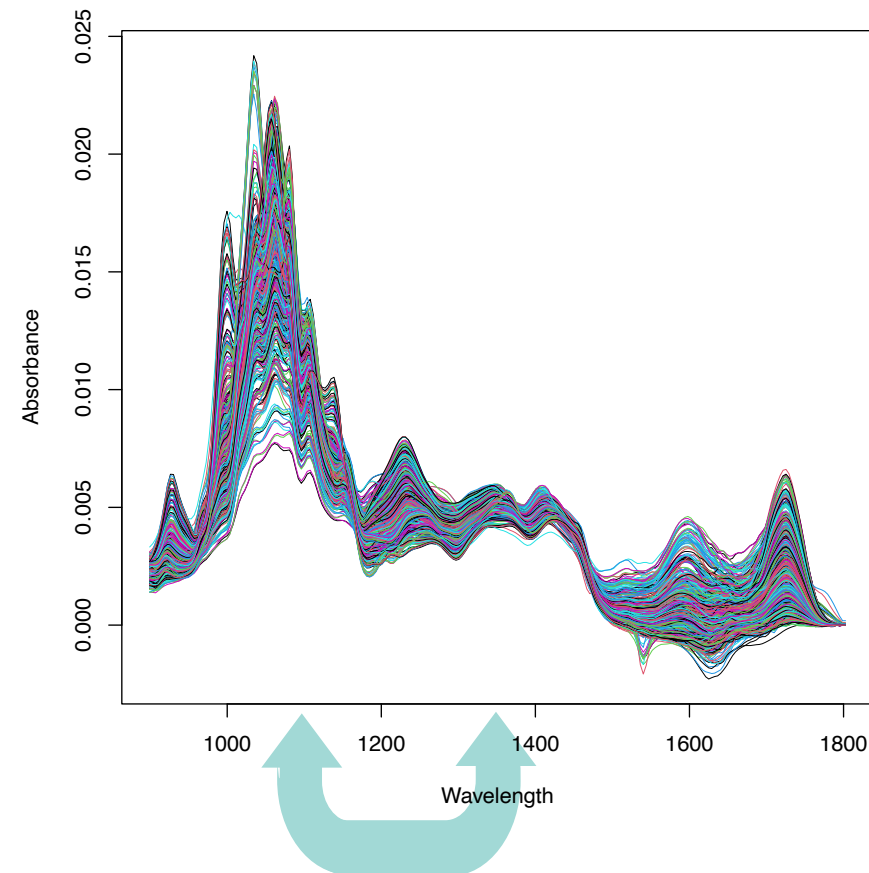
Example: fruit purees spectra



MOTIVATION

- **Aim:** to test (conditional) independence between different parts of the functions' domain.

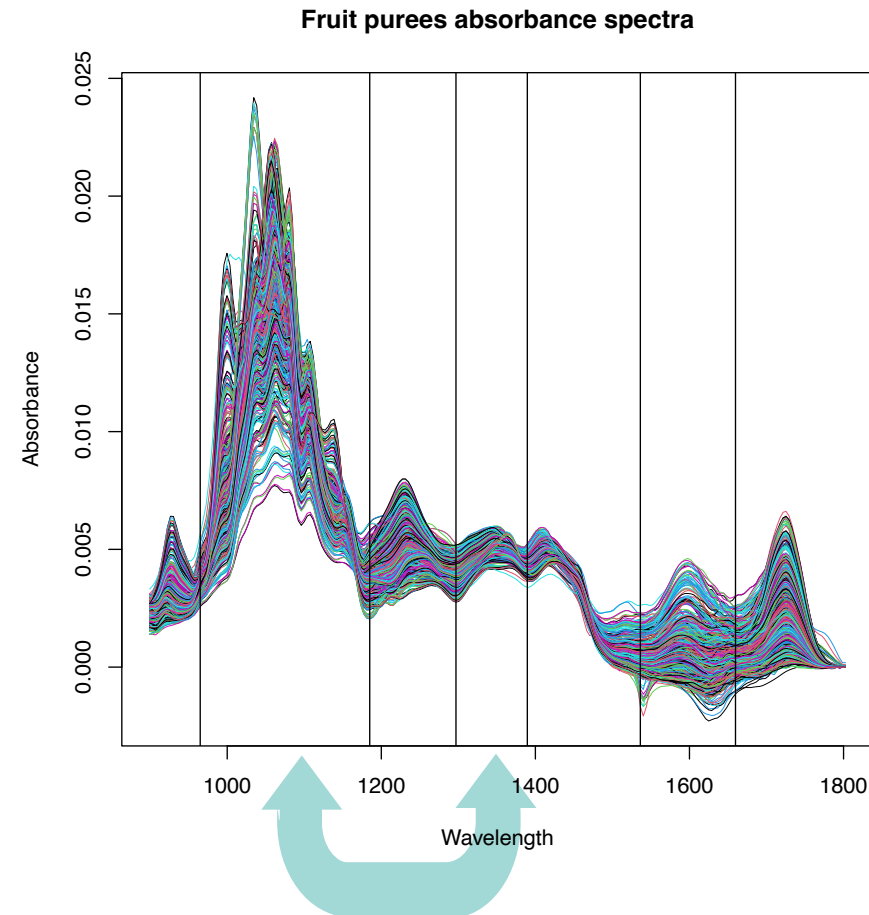
Example: fruit purees spectra



MOTIVATION

- **Aim:** to test (conditional) independence between different parts of the functions' domain.
- Assumption 1: the domain can be partitioned into regions of interest.

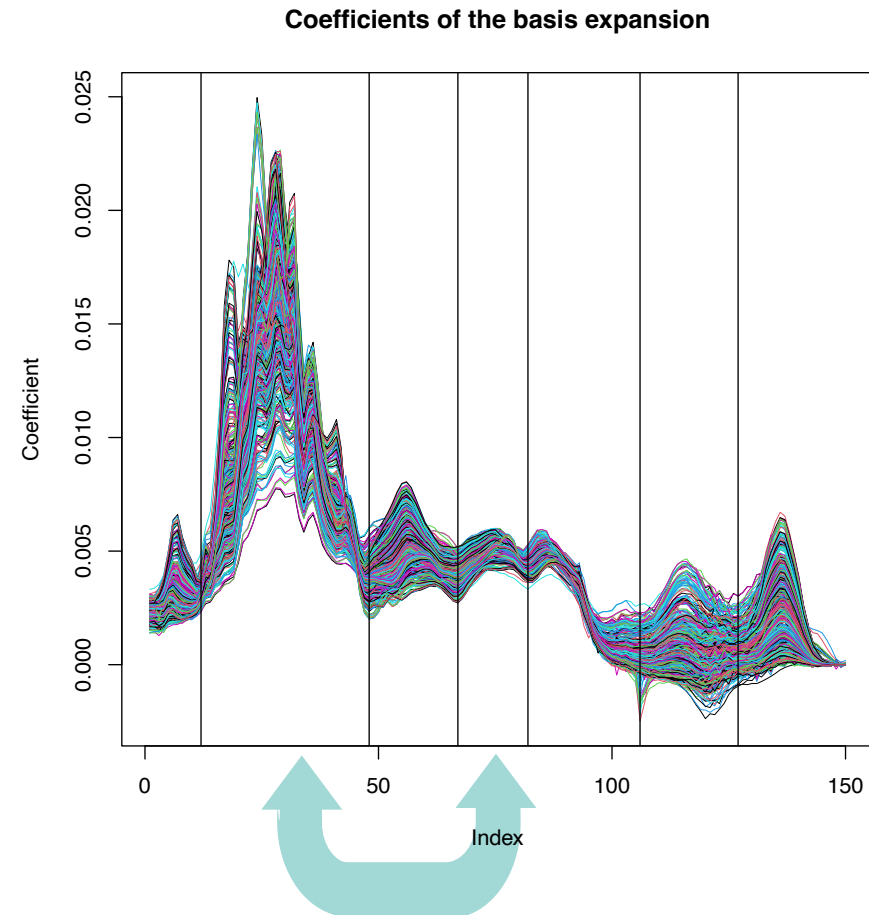
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MOTIVATION

- **Aim:** to test (conditional) independence between different parts of the functions' domain.
- Assumption 1: the domain can be partitioned into regions of interest.
- Assumption 2: data can be described with a B-splines basis expansion.
 - Coefficients are directly related to the parts of the domain.
 - A significant dependence between basis coefficients translates into a significant dependence between parts of the domain.

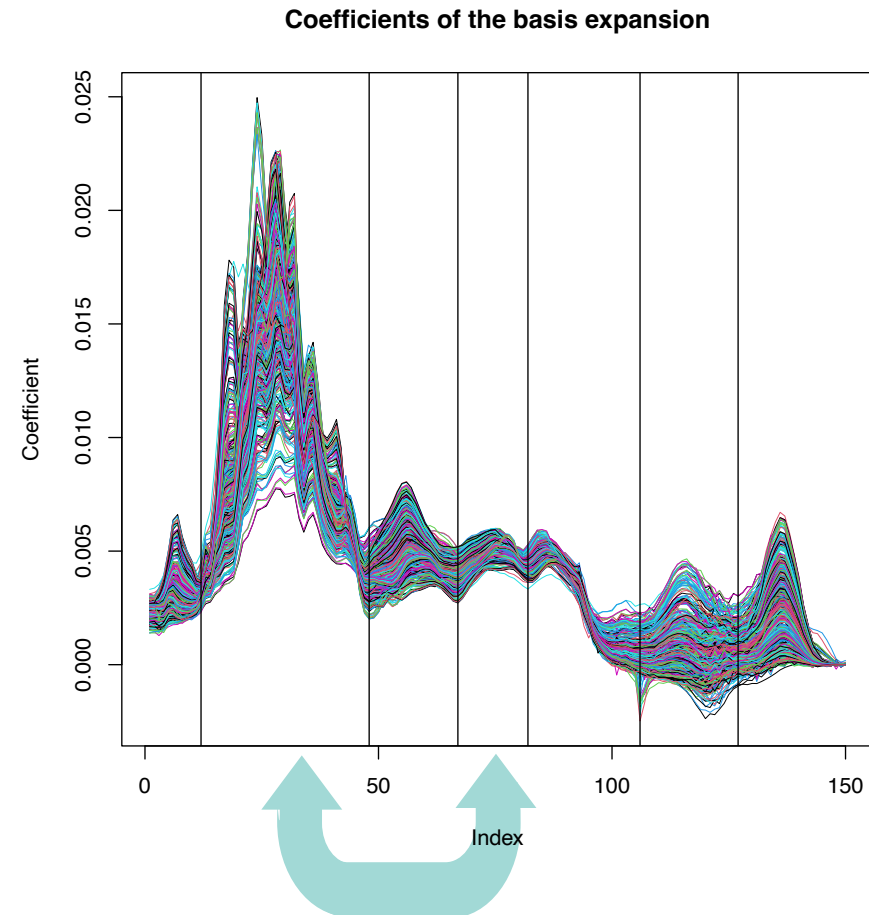
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- Assumption 1: the domain can be partitioned into regions of interest.
- Assumption 2: data can be described with a B-splines basis expansion.
 - Coefficients are directly related to the parts of the domain.
 - A significant dependence between basis coefficients translates into a significant dependence between parts of the domain.
- We look at the block structure of the covariance matrix (precision matrix) of the basis coefficients.

Example: fruit purees spectra



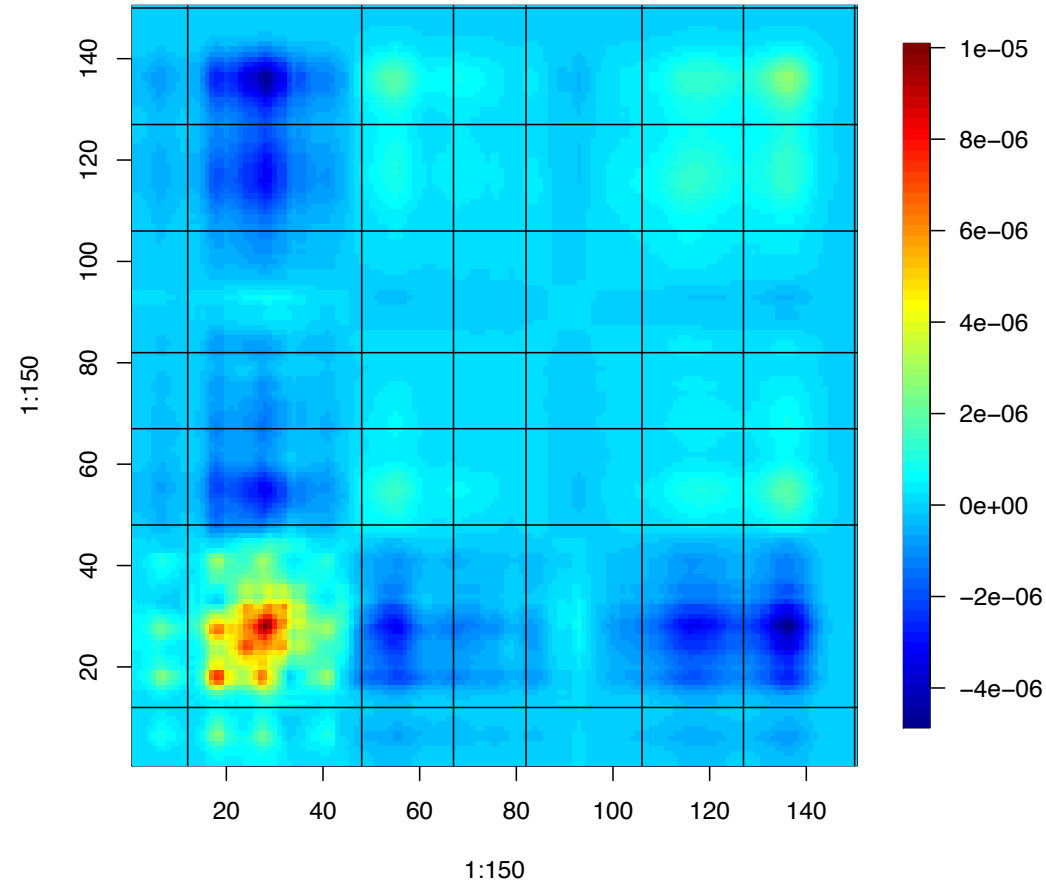
Linear dependence between two

RoI



Block of the covariance matrix $\neq 0$

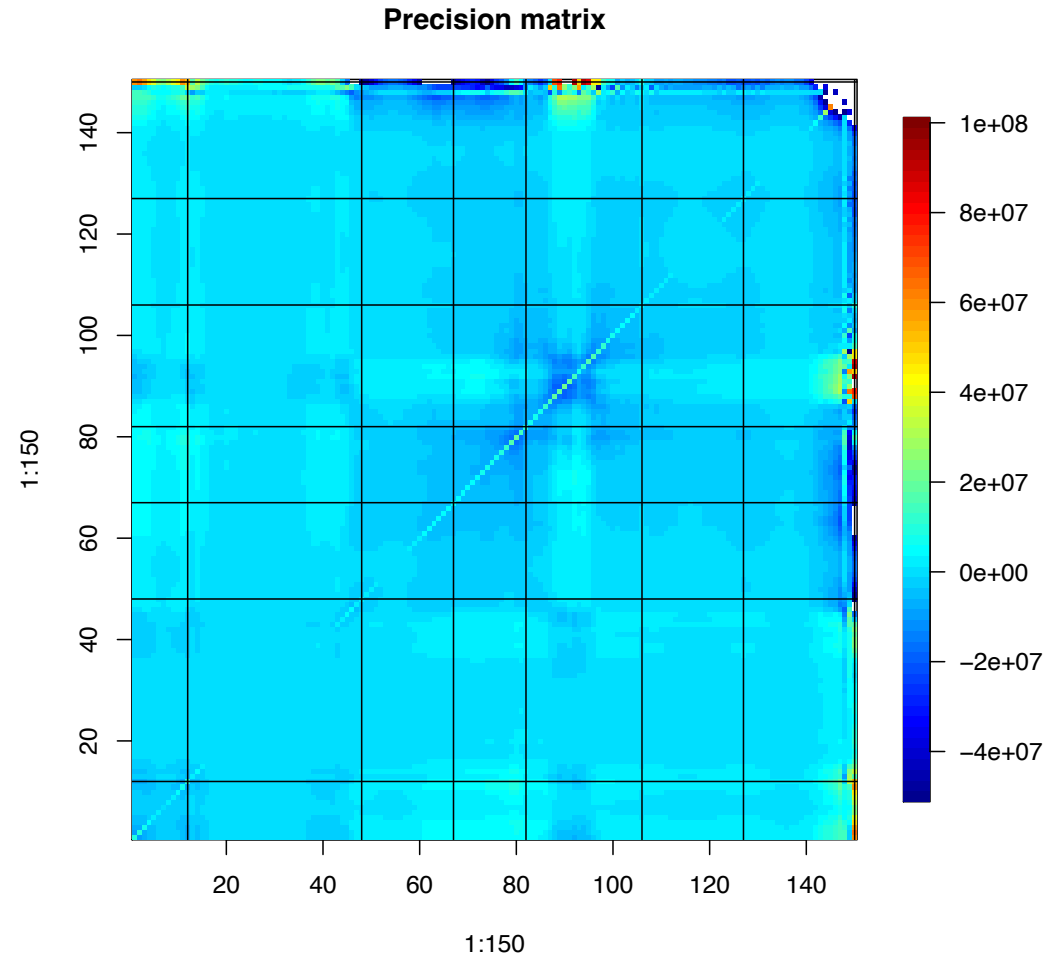
Covariance matrix



Conditional linear dependence
between two RoI



Block of the precision matrix $\neq 0$



Estimator proposed by Xia et al. (2018)

Functional data. We assume to observe functional data in $L^2(D)$ with $D \subset \mathbb{R}$

$$\mathbf{X}_1(t), \dots, \mathbf{X}_n(t) \quad t \in D, \mathbf{X}_i \in L^2(D)$$

Basis expansion.

$$\mathbf{X}_i(t) = \sum_{j=1}^p \phi_j(t) C_{ij} \quad (\mathbf{X}_1, \dots, \mathbf{X}_n) \Rightarrow (\mathbf{C}_1, \dots, \mathbf{C}_n)$$

Blocks. The coefficients $\{C_{ij}\}$ are partitioned into M blocks, associated to different RoI:

$$\mathcal{I}_1, \dots, \mathcal{I}_M \subset \{1, \dots, p\}$$

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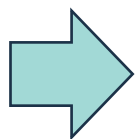
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Blocks. The coefficients $\{C_{ij}\}$ are partitioned into M blocks, associated to different RoI:

$$\mathcal{I}_1, \dots, \mathcal{I}_M \subset \{1, \dots, p\}$$



1. Test for a single block of the covariance (precision) matrix
2. Adjustment for taking into account block multiplicity

TEST ON A BLOCK OF THE COVARIANCE MATRIX

Permutation test of linear independence between coefficients in blocks $\mathcal{J}_m$ and $\mathcal{J}_{m'}$:

$$H_{0,m,m'} : \mathbf{C}_{\mathcal{J}'_m}, \mathbf{C}_{\mathcal{J}'_m} \text{ are independent} \quad H_{1,m,m'} : \Sigma_{\mathcal{J}_m \times \mathcal{J}'_m} \neq 0$$

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- **Test statistic:**

$$T_{mm'} = \sum_{j \in \mathcal{J}_m, j' \in \mathcal{J}_{m'}} \left(\frac{\hat{\Sigma}_{jj'}}{\sqrt{\hat{\Sigma}_{jj} \hat{\Sigma}_{j'j'}}} \right)^2$$

TEST ON A BLOCK OF THE COVARIANCE MATRIX

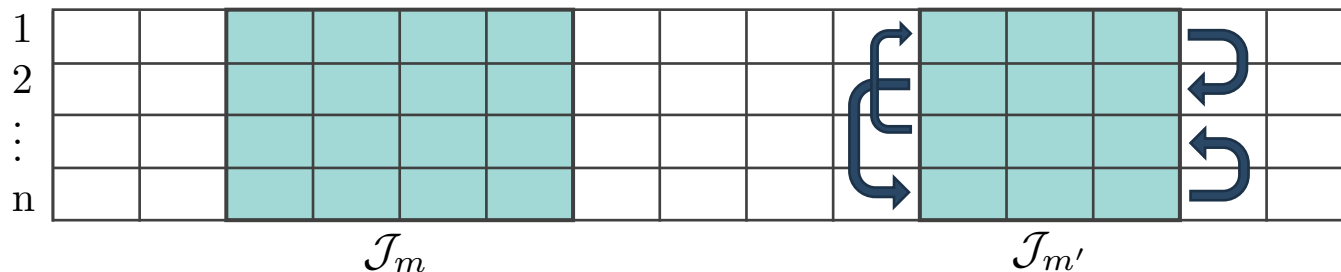
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- **Permutations:** $n!$ permutations of the coefficients C_{ij} $j \in \mathcal{J}_m$ keeping C_{ij} $j \in \mathcal{J}_{m'}$ fixed, (or vice-versa).



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- **Permutations:** $n!$ permutations of the coefficients C_{ij} $j \in \mathcal{J}_m$ keeping C_{ij} $j \in \mathcal{J}_{m'}$ fixed, (or vice-versa).

- **p-value:**

$$p_{m,m'} = \frac{\#\{T_{mm'}^* \geq T_{mm'}\}}{n!}$$

Test statistic evaluated on original data

Test statistic evaluated on permuted data

THEORETICAL PROPERTIES: TEST ON COVARIANCE MATRIX

- The test of linear independence is **exact**, but it might be **not consistent under general alternatives** (e.g., when the dependence is not linear):

$$\begin{aligned}\mathbb{P}_{H_{0,m,m'}}[p_{m,m'} \leq \alpha] &= \alpha \\ \lim_{n \rightarrow \infty} \mathbb{P}_{H_{1,m,m'}}[p_{m,m'} \leq \alpha] &= 1 \\ \lim_{n \rightarrow \infty} \mathbb{P}_{H_{0,m,m'}^C}[p_{m,m'} \leq \alpha] &\leq 1\end{aligned}$$

- For Gaussian data: the test of linear independence is a test for independence. It is **exact** for any sample size and **consistent** under every alternative.

$$\begin{aligned}\mathbb{P}_{H_{0,m,m'}}[p_{m,m'} \leq \alpha] &= \alpha \\ \lim_{n \rightarrow \infty} \mathbb{P}_{H_{1,m,m'}}[p_{m,m'} \leq \alpha] &= 1 \\ \lim_{n \rightarrow \infty} \mathbb{P}_{H_{0,m,m'}^C}[p_{m,m'} \leq \alpha] &= 1\end{aligned}$$

TEST ON A BLOCK OF THE PRECISION MATRIX

Permutation test of conditional linear independence between coefficients in blocks $\mathcal{J}_m$ and $\mathcal{J}_{m'}$:

$$H_{0,m,m'} : \begin{cases} \mathbf{C}_{\mathcal{J}_m} = \mathbf{C}_{\{1,\dots,p\} \setminus (\mathcal{J}_m \cup \mathcal{J}_{m'})} \mathbf{A} + \boldsymbol{\varepsilon}_{\mathcal{J}_m} \\ \mathbf{C}_{\mathcal{J}_{m'}} = \mathbf{C}_{\{1,\dots,p\} \setminus (\mathcal{J}_m \cup \mathcal{J}_{m'})} \mathbf{A}' + \boldsymbol{\varepsilon}_{\mathcal{J}_{m'}} \\ \boldsymbol{\varepsilon}_{\mathcal{J}_m}, \boldsymbol{\varepsilon}_{\mathcal{J}_{m'}} \quad \text{independent} \end{cases} \quad H_{1,m,m'} = \boldsymbol{\Omega}_{\mathcal{J}_m \times \mathcal{J}_{m'}} \neq 0$$

TEST ON A BLOCK OF THE PRECISION MATRIX

Permutation test of conditional linear independence between coefficients in blocks $\mathcal{J}_m$ and $\mathcal{J}_{m'}$:

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- **Test statistic:**

$$T_{mm'} = \sum_{j \in \mathcal{J}_m, j' \in \mathcal{J}_{m'}} \left(\hat{\Omega}_{jj'} \right)^2$$

- Xia Y., Cai T., Cai T.T. Multiple testing of submatrices of a precision matrix with applications to identification of between pathway interactions J. Am Stat. Assoc., 113(521), 328–339 (2018).

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- **Test statistic:**

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- **Permutations:** ~~$n!$ permutations of the coefficients $C_{ij} \ j \in \mathcal{J}_m$ keeping $C_{ij} \ j \in \mathcal{J}_{m'}$ fixed, (or vice-versa).~~



Data are no longer
independent under H_0 !

TEST ON A BLOCK OF THE PRECISION MATRIX

Permutation test of conditional linear independence between coefficients in blocks $\mathcal{J}_m$ and $\mathcal{J}_{m'}$:

$$H_{0,m,m'} : \begin{cases} \mathbf{C}_{\mathcal{J}_m} = \mathbf{C}_{\{1,\dots,p\} \setminus (\mathcal{J}_m \cup \mathcal{J}_{m'})} \mathbf{A} + \boldsymbol{\varepsilon}_{\mathcal{J}_m} \\ \mathbf{C}_{\mathcal{J}_{m'}} = \mathbf{C}_{\{1,\dots,p\} \setminus (\mathcal{J}_m \cup \mathcal{J}_{m'})} \mathbf{A}' + \boldsymbol{\varepsilon}_{\mathcal{J}_{m'}} \\ \boldsymbol{\varepsilon}_{\mathcal{J}_m}, \boldsymbol{\varepsilon}_{\mathcal{J}_{m'}} \text{ independent} \end{cases} \quad H_{1,m,m'} = \boldsymbol{\Omega}_{\mathcal{J}_m \times \mathcal{J}_{m'}} \neq 0$$

- **Test statistic:**

$$T_{mm'} = \sum_{j \in \mathcal{J}_m, j' \in \mathcal{J}_{m'}} \left(\hat{\Omega}_{jj'} \right)^2$$

 Under the null hypothesis the errors of those two linear models are exchangeable:

$$\begin{aligned} \mathbf{C}_{\mathcal{J}_m} &= \mathbf{C}_{\{1,\dots,p\} \setminus (\mathcal{J}_m \cup \mathcal{J}_{m'})} \mathbf{A} + \boldsymbol{\varepsilon}_{\mathcal{J}_m} \\ \mathbf{C}_{\mathcal{J}_{m'}} &= \mathbf{C}_{\{1,\dots,p\} \setminus (\mathcal{J}_m \cup \mathcal{J}_{m'})} \mathbf{A}' + \boldsymbol{\varepsilon}_{\mathcal{J}_{m'}} \end{aligned}$$

- **Permutations:** $n!$ permutations of the residuals $\hat{\varepsilon}_{ij}$ $j \in \mathcal{J}_m$ keeping $\hat{\varepsilon}_{ij}$ $j \in \mathcal{J}_{m'}$ fixed, (or vice-versa).

TEST ON A BLOCK OF THE PRECISION MATRIX

Permutation test of conditional linear independence between coefficients in blocks $\mathcal{J}_m$ and $\mathcal{J}_{m'}$:

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- **Test statistic:**

$$T_{mm'} = \sum_{j \in \mathcal{J}_m, j' \in \mathcal{J}_{m'}} \left(\hat{\Omega}_{jj'} \right)^2$$

- **Permutations:** $n!$ permutations of the residuals $\hat{\varepsilon}_{ij}$ $j \in \mathcal{J}_m$ keeping $\hat{\varepsilon}_{ij}$ $j \in \mathcal{J}_{m'}$ fixed, (or vice-versa).
- **p-value:**

$$p = \frac{\#\{T_{mm'}^* \geq T_{mm'}\}}{n!}$$

THEORETICAL PROPERTIES: TEST ON PRECISION MATRIX

- The test of conditional linear independence is **asymptotically exact** and **consistent**. However, only linear conditional independence is tested (which can not be generalized to conditional independence).

$$\lim_{n \rightarrow \infty} \mathbb{P}_{H_{0,m,m'}} [p_{m,m'} \leq \alpha] = \alpha$$
$$\lim_{n \rightarrow \infty} \mathbb{P}_{H_{1,m,m'}} [p_{m,m'} \leq \alpha] = 1$$

- For Gaussian data: the test of conditional linear independence is a test for conditional independence. It is **asymptotically exact** and **consistent** under every alternative.

MULTIPLE TESTING OF SUBMATRICES

The total number of tests is $M(M-1)/2$. So, we need to adjust p-values.

Available methods include Bonferroni adjustment (Holm, 1976), Closed Testing Procedure (Marcus et al, 1976), or methods specifically designed for the precision matrix (Xia et al. 2018):



generally very conservative;

do not exploit the proximity structure between blocks.

Instead, we generalize the interval-wise testing procedure (Pini and Vantini, 2016, 2017), a method to adjust for multiplicity controlling the FWER over closed sub-intervals of the domain.

- Holm, S.: A simple sequentially rejective multiple test procedure Scand. J. Stat., 6(2), 65–70 (1979)
- Marcus, R., Eric, P., & Gabriel, K. R. On closed testing procedures with special reference to ordered analysis of variance. *Biometrika*, 63(3), 655–660 (1976).
- Pini, A. and Vantini, S. The interval testing procedure: a general framework for inference in functional data analysis *Biometrics* 72(3) 835–845 (2016).
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MULTIPLE TESTING OF SUBMATRICES

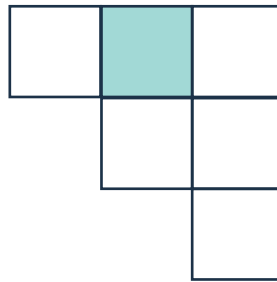
1. Perform a test on each couple of blocks.
2. Perform a tests on each couple of non-overlapping intervals of blocks.
3. For each couple of blocks $\mathcal{J}_m$ and $\mathcal{J}_{m'}$, compute the adjusted p -value as the maximum between all p -values of tests of intervals of blocks including $\mathcal{J}_m$ and $\mathcal{J}_{m'}$ (including blocks $\mathcal{J}_m$ and $\mathcal{J}_{m'}$ themselves).

$$\tilde{p}_{m,m'} = \max_{\substack{\mathcal{I}: m \in \mathcal{I} \\ \mathcal{I}': m' \in \mathcal{I}'}} p_{\mathcal{I}, \mathcal{I}'}$$

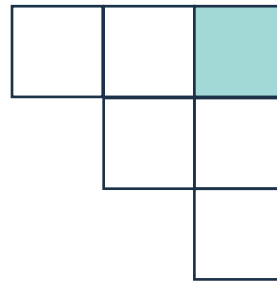
MULTIPLE TESTING OF SUBMATRICES

Example: three RoI

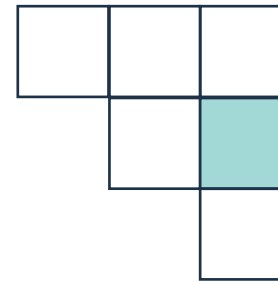
- Performed tests:



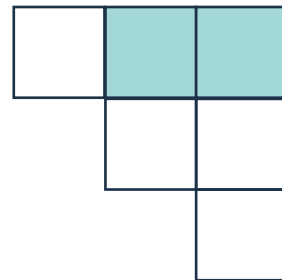
$H_{0_{1,2}}$ $H_{1_{1,2}}$



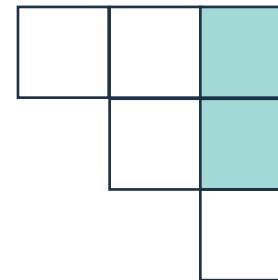
$H_{0_{1,3}}$ $H_{1_{1,3}}$



$H_{0_{2,3}}$ $H_{1_{2,3}}$



$H_{0_{1,(2,3)}}$ $H_{1_{1,(2,3)}}$



$H_{0_{(1,2),3}}$ $H_{1_{(1,2),3}}$

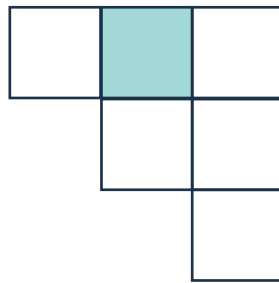


All tests can
be performed
with the same
procedure
described earlier

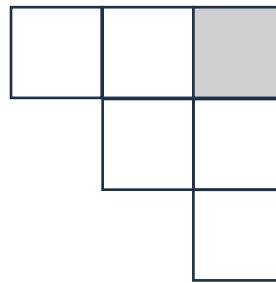
MULTIPLE TESTING OF SUBMATRICES

Example: three RoI

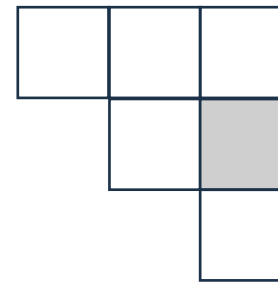
- Performed tests
- Adjusted p-value for couple (1,2):



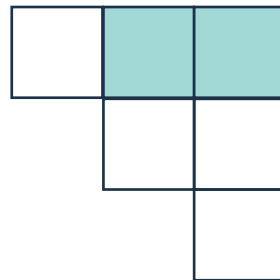
$H_{0_{1,2}}$ $H_{1_{1,2}}$



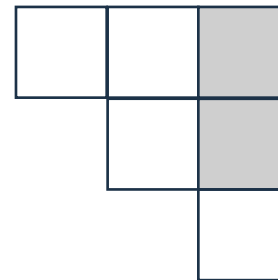
$H_{0_{1,3}}$ $H_{1_{1,3}}$



$H_{0_{2,3}}$ $H_{1_{2,3}}$



$H_{0_{1,(2,3)}}$ $H_{1_{1,(2,3)}}$



$H_{0_{(1,2),3}}$ $H_{1_{(1,2),3}}$

THEORETICAL PROPERTIES OF THE PROCEDURE

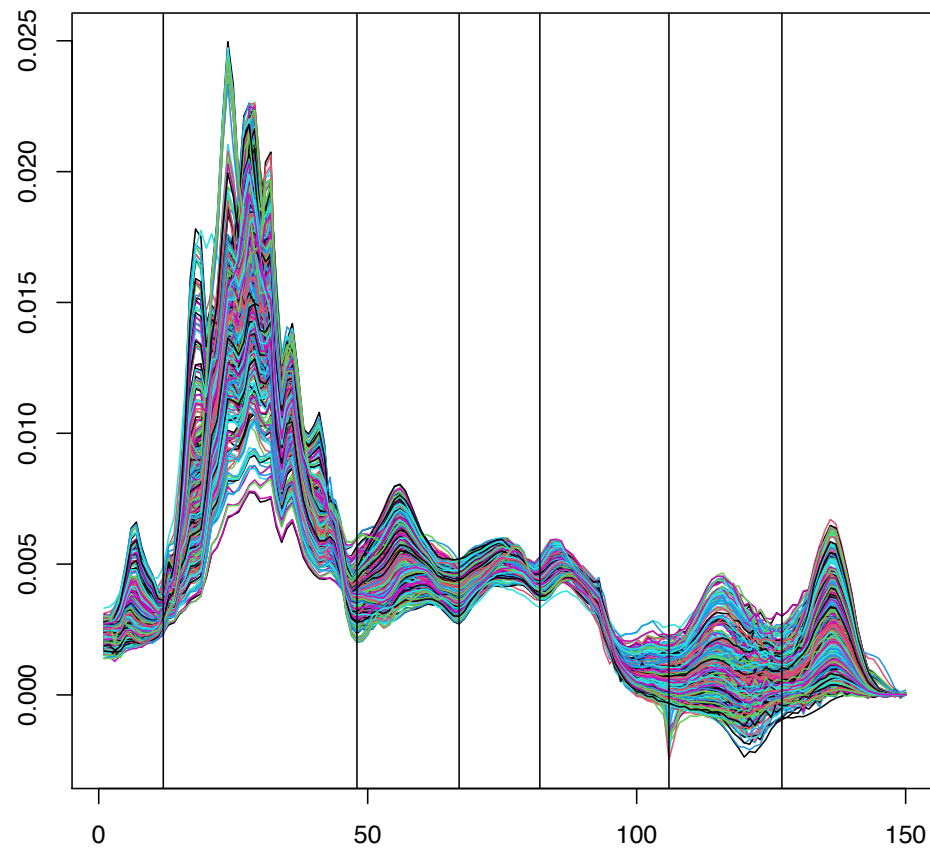
Theorem 1 *The adjusted p-value $\tilde{p}_{m,m'}$ is provided with the following error control: for all non-overlapping intervals of blocks $\mathcal{I} = \cup_{i=m}^{m+h} \{\mathcal{I}_i\}$ and $\mathcal{I}' = \cup_{i=m'}^{m'+h'} \{\mathcal{I}_i\}$, with $1 \leq m \leq m+h < m' \leq m'+h' \leq M$, $\forall \alpha \in (0, 1)$*

$$\begin{aligned} & \text{if } H_{0,m,m'} \text{ is true } \forall (m, m') \in \mathcal{I} \times \mathcal{I}', \\ & \limsup_{n \rightarrow \infty} \mathbb{P} [\exists (m, m') \in \mathcal{I} \times \mathcal{I}' : \tilde{p}_{m,m'} \leq \alpha] \leq \alpha. \end{aligned}$$

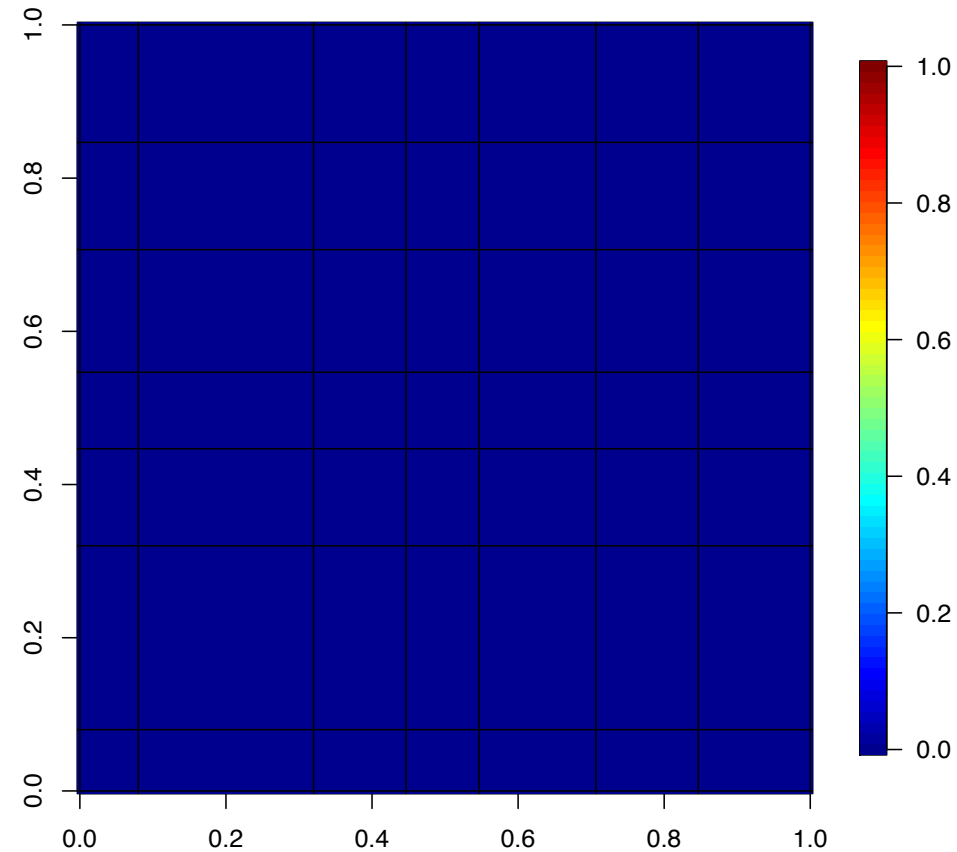
Theorem 2 *The adjusted p-value $\tilde{p}_{m,m'}$ is consistent, that is: for all non-overlapping intervals of blocks $\mathcal{I} = \cup_{i=m}^{m+h} \{\mathcal{I}_i\}$ and $\mathcal{I}' = \cup_{i=m'}^{m'+h'} \{\mathcal{I}_i\}$, with $1 \leq m \leq m+h < m' \leq m'+h' \leq M$, $\forall \alpha \in (0, 1)$*

$$\begin{aligned} & \text{if } H_{0,m,m'} \text{ is false } \forall (m, m') \in \mathcal{I} \times \mathcal{I}', \\ & \lim_{n \rightarrow \infty} \mathbb{P} [\forall (m, m') \in \mathcal{I} \times \mathcal{I}' : \tilde{p}_{m,m'} \leq \alpha] = 1. \end{aligned}$$

FRUITS PUREES DATASET INDEPENDENCE

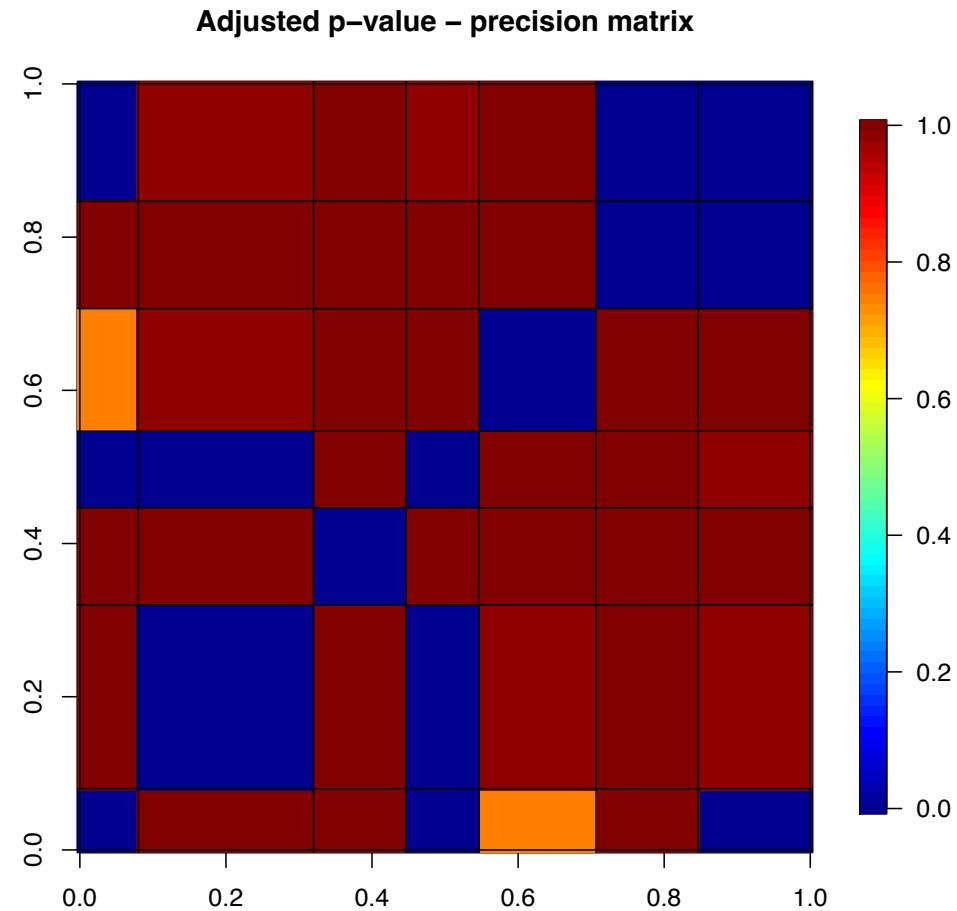
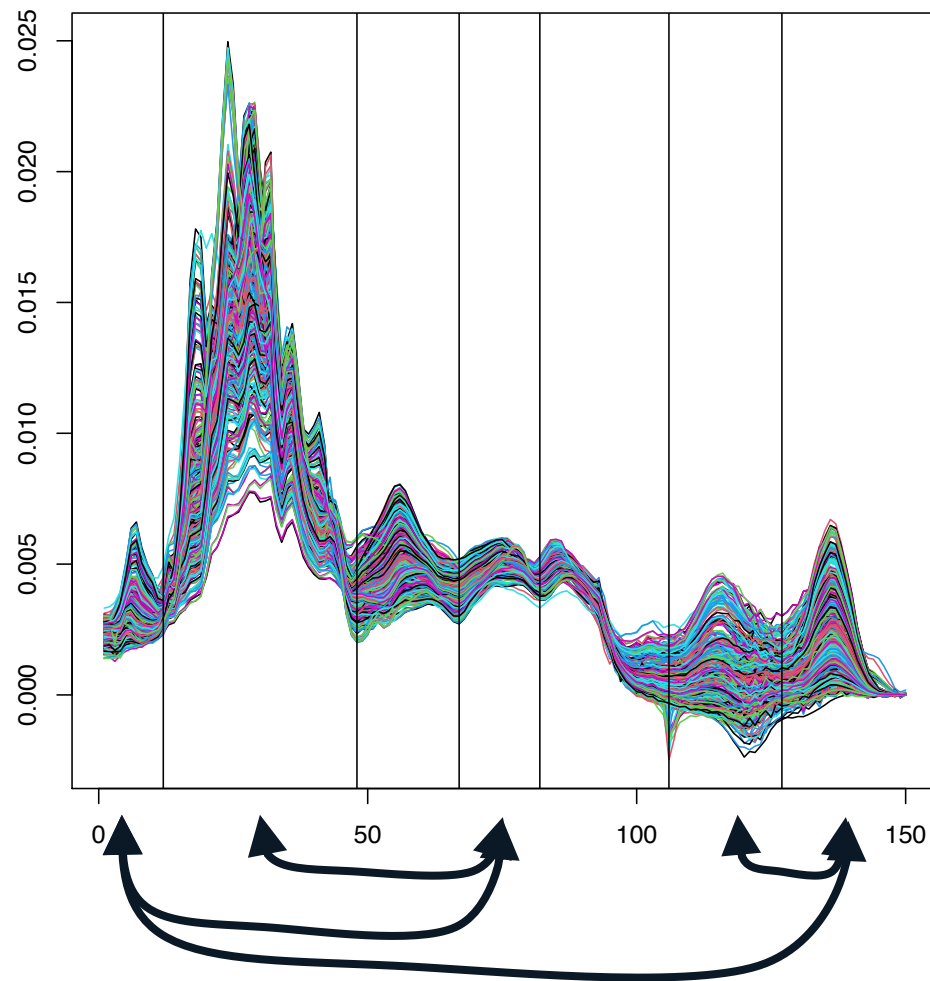


Adjusted p-value – covariance matrix



FRUITS PUREES DATASET

CONDITIONAL INDEPENDENCE



DISCUSSION

- Two methods for performing inference on the covariance structure of functional data:
 - A test of linear independence.
 - test of conditional linear independence.
- A novel way to adjust for multiplicity when testing blocks of the covariance/precision matrix.
- The adjustment method can be plugged-in with every available testing procedure.



Future works

- How to define blocks when they are not available?
- How to extend the procedure without relying on a basis expansion?

SELECTED REFERENCES

- Briandet, R., Kemsley, E. K., & Wilson, R. H. Approaches to adulteration detection in instant coffees using infrared spectroscopy and chemometrics. *Journal of the Science of Food and Agriculture*, 71(3), 359-366 (1996).
- Freedman, D., Lane, D. A nonstochastic interpretation of reported significance levels *Journal of Business & Economic Statistics*, 1(4), 292–298 (1983).
- Holm, S.: A simple sequentially rejective multiple test procedure *Scand. J. Stat.*, 6(2), 65–70 (1979)
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