Package ‘TestCor’

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Title FWER and FDR Controlling Procedures for Multiple Correlation Tests

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Description Different multiple testing procedures for correlation tests are implemented. These procedures were shown to theoretically control asymptotically the Family Wise Error Rate (Roux (2018) <https://tel.archives-ouvertes.fr/tel-01971574v1>) or the False Discovery Rate (Cai & Liu (2016) <doi:10.1080/01621459.2014.999157>). The package gather four test statistics used in correlation testing, four FWER procedures with either single step or stepdown versions, and four FDR procedures.

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`TestCor-package` *FWER and FDR controlling procedures for multiple correlation tests*

Description

The package compiles some multiple testing procedures which theoretically control asymptotically the FWER in the framework of correlation testing. Four tests statistics can be considered: the empirical correlation, the Student statistics, the Fisher's z-transform and the usual Gaussian statistics considering random variables $(X_i - mean(X_i))(X_j - mean(X_j))$. Four methods are implemented: Bonferroni (1935)'s, Šidák (1967)'s, Romano & Wolf (2005)'s bootstrap and (Drton & Perlman (2007)'s procedure based on the asymptotic distributions of the test statistics, called MaxTinfty. The package also includes some multiple testing procedures which are related to the control of the FDR : Cai & Liu (2016)'s procedures called LCT-N and LCT-B -which have been proven to control the FDR for correlation tests- and Benjamini & Hochberg (1995)'s -which has no theoretical results in correlation testing.

Details

Consider $\{\boldsymbol{X}_\ell = (X_{1\ell}, \dots X_{p\ell}),\ \ell = 1, ..., n\}$ a set of n independent and identically distributed R^p-valued random variables. Denote `data` the array containing $\{\mathbf{X}_\ell,\ \ell = 1, \dots, n\}$, with observation indexes l in row. The aim is to test simultaneously

$$(H_{0ij})\ Cor(X_i, X_j) = 0\ \ against\ \ (H_{1ij})\ Cor(X_i, X_j) \neq 0,\ \ i, j = 1, ..., p,\ i < j.$$

Four tests statistics are implemented: the empirical correlation, the Student statistics, the Fisher's z-transform and the usual test statistics on expectancy considering the product of random variables. They are available in function `eval_stat`. Next, two main types of procedures are available:

Asymptotically FWER controlling procedures: Bonferroni (1935)'s method, Šidák (1967)'s procedure, Romano & Wolf (2005)'s bootstrap procedure and Drton & Perlman (2007)'s procedure. A description of these methods can be found in Chapter 5 of Roux (2018). To apply these procedures, function `ApplyFwerCor` can be used as follows:

`ApplyFwerCor(data,alpha,stat_test,method)`, with `alpha` the desired level of control for FDR and `stat_test`, `method` respectively the kind of test statistic and the FDR controlling method. The function returns the list of indexes $\{(i,j), i<j\}$ for which null hypothesis (H_{0ij}) is rejected.

Asymptotically FDR controlling procedures: Cai & Liu(2016)'s two procedures and Benjamini & Hochberg (1995)'s procedure (with no theoretical proof for the latest). To apply these procedures, use function `ApplyFdrCor` as follows: `ApplyFdrCor(data,alpha,stat_test,method)` with `alpha` the desired level of control for FWER and `stat_test`, `method` respectively the kind of test statistic and the FDR controlling method. The function returns the list of indexes $\{(i,j), i<j\}$ for which null hypothesis (H_{0ij}) is rejected.

Functions `SimuFwer` and `SimuFdr` provide simulations of Gaussian random variables for a given correlation matrix and return estimated FWER, FDR, Power and true discovery rate obtained applying one of the procedure above. Some example of results obtained can be found in Chapter 6 of Roux (2018).

Author(s)

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References

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. Journal of the royal statistical society. Series B (Methodological), 289-300, https://doi.org/10.1111/j.2517-6161.1995.tb02031.x.

Bonferroni, C. E. (1935). Il calcolo delle assicurazioni su gruppi di teste. Studi in onore del professore salvatore ortu carboni, 13-60.

Cai, T. T., & Liu, W. (2016). Large-scale multiple testing of correlations. Journal of the American Statistical Association, 111(513), 229-240, https://doi.org/10.1080/01621459.2014.999157.

Drton, M., & Perlman, M. D. (2007). Multiple testing and error control in Gaussian graphical model selection. Statistical Science, 22(3), 430-449, https://doi.org/10.1214/088342307000000113.

Romano, J. P., & Wolf, M. (2005). Exact and approximate stepdown methods for multiple hypothesis testing. Journal of the American Statistical Association, 100(469), 94-108, https://doi.org/10.1198/016214504000000539.

Roux, M. (2018). Graph inference by multiple testing with application to Neuroimaging, Ph.D., Université Grenoble Alpes, France, https://tel.archives-ouvertes.fr/tel-01971574v1.

Šidák, Z. (1967). Rectangular confidence regions for the means of multivariate normal distributions. Journal of the American Statistical Association, 62(318), 626-633.

Examples

```
# Parameters for simulations
Nsimu  <- 100               # number of Monte-Carlo simulations
seqn   <- seq(100,400,100)  # sample sizes
p      <- 10                # number of random variables considered
rho    <- 0.3               # value of non-zero correlations
seed   <- 156724

corr_theo <- diag(1,p)      # the correlation matrix
corr_theo[1,2:p] <- rho
corr_theo[2:p,1] <- rho

# Parameters for multiple testing procedure
stat_test <- 'empirical'    # test statistics for correlation tests
method <- 'BootRW'          # FWER controlling procedure
SD <- FALSE                 # logical determining if stepdown is applied
alpha  <- 0.05              # FWER threshold
Nboot  <- 100               # number of bootstrap or simulated samples

# Simulations and application of the chosen procedure
res <- matrix(0,nrow=length(seqn),ncol=4)
for(i in 1:length(seqn)){
    temp <- SimuFwer(corr_theo,n=seqn[i],Nsimu=Nsimu,alpha=alpha,stat_test=stat_test,
           method='BootRW',Nboot=Nboot,stepdown=SD,seed=seed)
    res[i,] <- temp
}
rownames(res) <- seqn
colnames(res) <- names(temp)

# Display results
par(mfrow=c(1,2))
plot(seqn,res[,'fwer'],type='b',ylim=c(0,max(alpha*1.1,max(res[,'fwer']))),
    main='FWER',ylab='fwer',xlab='number of observations')
plot(seqn,res[,'power'],type='b',ylim=c(0,1.1),
    main='Power',ylab='power',xlab='number of observations')
```

`ApplyFdrCor` *Applies multiple testing procedures built to control (asymptotically) the FDR for correlation testing.*

Description

Applies multiple testing procedures built to control (asymptotically) the FDR for correlation testing. Some have no theoretical proofs for tests on a correlation matrix.

Usage

```
ApplyFdrCor(data, alpha = 0.05, stat_test = "empirical",
  method = "LCTnorm", Nboot = 1000, vect = FALSE)
```

Arguments

`data`	matrix of observations
`alpha`	level of multiple testing
`stat_test`	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1 + corr)/(1 - corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt{(}1 - corr^2)$ **'gaussian'** $\sqrt{n}*mean(Y)/sd(Y)$ with $Y = (X_i - mean(X_i))(X_j - mean(X_j))$
`method`	choice between 'LCTnorm' and 'LCTboot' developped by Cai & Liu (2016), 'BH', traditional Benjamini-Hochberg's procedure Benjamini & Hochberg (1995)'s and 'BHboot', Benjamini-Hochberg (1995)'s procedure with bootstrap evaluation of p-values
`Nboot`	number of iterations for bootstrap p-values evaluation
`vect`	if TRUE returns a vector of TRUE/FALSE values, corresponding to `vectorize(cor(data))`; if FALSE, returns an array containing rows and columns of significative correlations

Value

Returns the list of significative correlations according to the multiple testing procedure applied.

References

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. Journal of the royal statistical society. Series B (Methodological), 289-300.

Cai, T. T., & Liu, W. (2016). Large-scale multiple testing of correlations. Journal of the American Statistical Association, 111(513), 229-240.

Roux, M. (2018). Graph inference by multiple testing with application to Neuroimaging, Ph.D., Université Grenoble Alpes, France, https://tel.archives-ouvertes.fr/tel-01971574v1.

See Also

ApplyFwerCor

LCTnorm, LCTboot, BHCor, BHBootCor

Examples

```
n <- 100
p <- 10
corr_theo <- diag(1,p)
data <- MASS::mvrnorm(n,rep(0,p),corr_theo)
alpha <- 0.05
res <- ApplyFdrCor(data,alpha,stat_test='empirical',method='LCTnorm')
```

ApplyFwerCor *Applies multiple testing procedures controlling (asymptotically) the FWER for tests on a correlation matrix.*

Description

Applies multiple testing procedures controlling (asymptotically) the FWER for tests on a correlation matrix. Methods are described in Chapter 5 of *roux*.

Usage

```
ApplyFwerCor(data, alpha = 0.05, stat_test = "empirical",
  method = "MaxTinfty", Nboot = 1000, stepdown = TRUE,
  vect = FALSE)
```

Arguments

`data`	matrix of observations
`alpha`	level of multiple testing
`stat_test`	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1+corr)/(1-corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt{(}1-corr^2)$ **'gaussian'** $\sqrt{n}*mean(Y)/sd(Y)$ with $Y=(X_i-mean(X_i))(X_j-mean(X_j))$
`method`	choice between 'Bonferroni', 'Sidak', 'BootRW', 'MaxTinfty'
`Nboot`	number of iterations for Monte-Carlo of bootstrap quantile evaluation
`stepdown`	logical, if TRUE a stepdown procedure is applied
`vect`	if TRUE returns a vector of TRUE/FALSE values, corresponding to `vectorize(cor(data))`; if FALSE, returns an array containing rows and columns of significative correlations

Value

Returns the list of significative correlations according to the multiple testing procedure applied

References

Bonferroni, C. E. (1935). Il calcolo delle assicurazioni su gruppi di teste. Studi in onore del professore salvatore ortu carboni, 13-60.

Drton, M., & Perlman, M. D. (2007). Multiple testing and error control in Gaussian graphical model selection. Statistical Science, 22(3), 430-449.

Romano, J. P., & Wolf, M. (2005). Exact and approximate stepdown methods for multiple hypothesis testing. Journal of the American Statistical Association, 100(469), 94-108.

Roux, M. (2018). Graph inference by multiple testing with application to Neuroimaging, Ph.D., Université Grenoble Alpes, France, https://tel.archives-ouvertes.fr/tel-01971574v1.

Šidák, Z. (1967). Rectangular confidence regions for the means of multivariate normal distributions. Journal of the American Statistical Association, 62(318), 626-633.

See Also

ApplyFwerCor_SD, ApplyFdrCor

BonferroniCor, SidakCor, BootRWCor, maxTinftyCor

BonferroniCor_SD, SidakCor_SD, BootRWCor_SD, maxTinftyCor_SD

Examples

```
n <- 100
p <- 10
corr_theo <- diag(1,p)
data <- MASS::mvrnorm(n,rep(0,p),corr_theo)
alpha <- 0.05
res <- ApplyFwerCor(data,alpha,stat_test='empirical',method='Bonferroni',stepdown=FALSE)
```

`ApplyFwerCor_oracle` *Applies an oracle version of MaxTinfty procedure described in Drton & Perlman (2007) for correlation testing.*

Description

Applies oracle MaxTinfty procedure described in Drton & Perlman (2007) which controls asymptotically the FWER for tests on a correlation matrix. It needs the true correlation matrix.

Usage

```
ApplyFwerCor_oracle(data, corr_theo, alpha = 0.05,
  stat_test = "empirical", method = "MaxTinfty", Nboot = 1000,
  stepdown = TRUE, vect = FALSE)
```

Arguments

`data`	matrix of observations
`corr_theo`	true matrix of corrlations
`alpha`	level of multiple testing
`stat_test`	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1 + corr)/(1 - corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt{(}1 - corr^2)$ **'gaussian'** $\sqrt{n}*mean(Y)/sd(Y)$ with $Y = (X_i-mean(X_i))(X_j-mean(X_j))$
`method`	only 'MaxTinfty' implemented
`Nboot`	number of iterations for Monte-Carlo of bootstrap quantile evaluation
`stepdown`	logical, if TRUE a stepdown procedure is applied if FALSE, returns an array containing rows and columns of significative correlations
`vect`	optional, logical, if TRUE returns a vector of TRUE/FALSE values, corresponding to `vectorize(cor(data))`; if FALSE, returns an array containing rows and columns of significative correlations

Value

Returns the list of significative correlations according to the multiple testing procedure applied Oracle estimation of the quantile is used, based on the true correlation matrix

References

Drton, M., & Perlman, M. D. (2007). Multiple testing and error control in Gaussian graphical model selection. Statistical Science, 22(3), 430-449.

Roux, M. (2018). Graph inference by multiple testing with application to Neuroimaging, Ph.D., Université Grenoble Alpes, France, https://tel.archives-ouvertes.fr/tel-01971574v1.

See Also

ApplyFwerCor

maxTinftyCor, maxTinftyCor_SD

Examples

```
n <- 100
p <- 10
corr_theo <- diag(1,p)
data <- MASS::mvrnorm(n,rep(0,p),corr_theo)
alpha <- 0.05
res <- ApplyFwerCor_oracle(data,corr_theo,alpha,stat_test='empirical',Nboot=1000,stepdown=FALSE)
```

`BHBootCor` *Benjamini & Hochberg (1995)'s procedure for correlation testing with bootstrap evaluation of p-values.*

Description

Benjamini & Hochberg (1995)'s procedure on the correlation matrix entries with bootstrap evaluation of p-values (no theoretical proof of control).

Usage

```
BHBootCor(data, alpha = 0.05, stat_test = "gaussian", Nboot = 100,
  vect = FALSE)
```

Arguments

`data`	matrix of observations
`alpha`	level of multiple testing
`stat_test`	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1+corr)/(1-corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt{(}1-corr^2)$

'gaussian' $\sqrt{n}*mean(Y)/sd(Y)$ with $Y = (X_i - mean(X_i))(X_j - mean(X_j))$

`Nboot` number of iterations for bootstrap quantile evaluation

`vect` if TRUE returns a vector of TRUE/FALSE values, corresponding to `vectorize(cor(data))`; if FALSE, returns an array containing rows and columns of significative correlations

Value

Returns

- a vector of logicals, equal to TRUE if the corresponding element of the statistic vector is rejected, if `vect=TRUE`,
- a vector containing indexes $\{(i, j),\ i < j\}$ for which correlation between variables i and j is significative, if `vect=FALSE`.

References

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. Journal of the royal statistical society. Series B (Methodological), 289-300.

See Also

ApplyFdrCor, BHCor

Examples

```
n <- 100
p <- 10
corr_theo <- diag(1,p)
data <- MASS::mvrnorm(n,rep(0,p),corr_theo)
alpha <- 0.05
res <- BHBootCor(data,alpha,stat_test='empirical')
```

BHCor *Benjamini & Hochberg (1995)'s procedure for correlation testing.*

Description

Benjamini & Hochberg (1995)'s procedure on the correlation matrix entries (no theoretical proof of control).

Usage

```
BHCor(data, alpha = 0.05, stat_test = "gaussian", vect = FALSE)
```

Arguments

`data`	matrix of observations
`alpha`	level of multiple testing
`stat_test`	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1 + corr)/(1 - corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt{(}1 - corr^2)$ **'gaussian'** $\sqrt{n}*mean(Y)/sd(Y)$ with $Y = (X_i - mean(X_i))(X_j - mean(X_j))$
`vect`	if TRUE returns a vector of TRUE/FALSE values, corresponding to vectorize(cor(data)) if FALSE, returns an array containing rows and columns of significative correlations

Value

Returns

- a vector of logicals, equal to TRUE if the corresponding element of the statistic vector is rejected, if `vect=TRUE`,
- a vector containing indexes $\{(i, j),\, i < j\}$ for which correlation between variables i and j is significative, if `vect=FALSE`.

References

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. Journal of the royal statistical society. Series B (Methodological), 289-300.

See Also

ApplyFdrCor, BHBootCor

Examples

```
n <- 100
p <- 10
corr_theo <- diag(1,p)
data <- MASS::mvrnorm(n,rep(0,p),corr_theo)
alpha <- 0.05
res <- BHCor(data,alpha,stat_test='empirical')
```

`BonferroniCor` *Bonferroni multiple testing procedure for correlations.*

Description

Bonferroni multiple testing procedure for correlations.

Usage

```
BonferroniCor(data, alpha = 0.05, stat_test = "empirical",
  vect = FALSE)
```

Arguments

`data`	matrix of observations
`alpha`	level of multiple testing
`stat_test`	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1 + corr)/(1 - corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt{(1 - corr^2)}$ **'gaussian'** $\sqrt{n} * mean(Y)/sd(Y)$ with $Y = (X_i - mean(X_i))(X_j - mean(X_j))$
`vect`	if TRUE returns a vector of TRUE/FALSE values, corresponding to `vectorize(cor(data))`; if FALSE, returns an array containing rows and columns of significative correlations

Value

Returns

- a vector of logicals, equal to TRUE if the corresponding element of the statistic vector is rejected, if `vect=TRUE`,
- a vector containing indexes $\{(i, j),\ i < j\}$ for which correlation between variables i and j is significative, if `vect=FALSE`.

References

Bonferroni, C. E. (1935). Il calcolo delle assicurazioni su gruppi di teste. Studi in onore del professore salvatore ortu carboni, 13-60.

Roux, M. (2018). Graph inference by multiple testing with application to Neuroimaging, Ph.D., Université Grenoble Alpes, France, https://tel.archives-ouvertes.fr/tel-01971574v1.

See Also

ApplyFwerCor, BonferroniCor_SD

Examples

```
n <- 100
p <- 10
corr_theo <- diag(1,p)
data <- MASS::mvrnorm(n,rep(0,p),corr_theo)
corr_mat <- cor(data)
corr_vect <- corr_mat[upper.tri(corr_mat)]
alpha <- 0.05
res <- BonferroniCor(data,alpha,stat_test='empirical')
```

BonferroniCor_SD *Bonferroni multiple testing method for correlations with stepdown procedure.*

Description

Bonferroni multiple testing method for correlations with stepdown procedure.

Usage

```
BonferroniCor_SD(data, alpha, stat_test = "empirical", vect = FALSE)
```

Arguments

data	matrix of observations
alpha	level of multiple testing
stat_test	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1 + corr)/(1 - corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt{(}1 - corr^2)$ **'gaussian'** $\sqrt{n}*mean(Y)/sd(Y)$ with $Y = (X_i - mean(X_i))(X_j - mean(X_j))$
vect	if TRUE returns a vector of TRUE/FALSE values, corresponding to `vectorize(cor(data))`; if FALSE, returns an array containing rows and columns of significative correlations

Value

Returns

- a vector of logicals, equal to TRUE if the corresponding element of the statistic vector is rejected, if `vect=TRUE`,
- a vector containing indexes $\{(i, j),\ i < j\}$ for which correlation between variables i and j is significative, if `vect=FALSE`.

References

Bonferroni, C. E. (1935). Il calcolo delle assicurazioni su gruppi di teste. Studi in onore del professore salvatore ortu carboni, 13-60.

Roux, M. (2018). Graph inference by multiple testing with application to Neuroimaging, Ph.D., Université Grenoble Alpes, France, https://tel.archives-ouvertes.fr/tel-01971574v1.

See Also

ApplyFwerCor, BonferroniCor

Examples

```
n <- 100
p <- 10
corr_theo <- diag(1,p)
data <- MASS::mvrnorm(n,rep(0,p),corr_theo)
alpha <- 0.05
res <- BonferroniCor_SD(data,alpha,stat_test='empirical')
```

BootRWCor   *Bootstrap multiple testing method of Romano & Wolf (2005) for correlations.*

Description

Multiple testing method based on the evaluation of quantile by bootstrap in the initial dataset (Romano & Wolf (2005)).

Usage

```
BootRWCor(data, alpha = 0.05, stat_test = "empirical", Nboot = 1000,
  vect = FALSE)
```

Arguments

data	matrix of observations
alpha	level of multiple testing
stat_test	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1+corr)/(1-corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt(1-corr^2)$ **'gaussian'** $\sqrt{n}*mean(Y)/sd(Y)$ with $Y = (X_i - mean(X_i))(X_j - mean(X_j))$
Nboot	number of iterations for Bootstrap quantile evaluation
vect	if TRUE returns a vector of TRUE/FALSE values, corresponding to `vectorize(cor(data))`; if FALSE, returns an array containing rows and columns of significative correlations

Value

Returns

- a vector of logicals, equal to TRUE if the corresponding element of the statistic vector is rejected, if `vect=TRUE`,
- a vector containing indexes $\{(i, j),\ i < j\}$ for which correlation between variables i and j is significative, if `vect=FALSE`.

References

Romano, J. P., & Wolf, M. (2005). Exact and approximate stepdown methods for multiple hypothesis testing. Journal of the American Statistical Association, 100(469), 94-108.

Roux, M. (2018). Graph inference by multiple testing with application to Neuroimaging, Ph.D., Université Grenoble Alpes, France, https://tel.archives-ouvertes.fr/tel-01971574v1.

See Also

ApplyFwerCor, BootRWCor_SD

Examples

```
n <- 100
p <- 10
corr_theo <- diag(1,p)
data <- MASS::mvrnorm(n,rep(0,p),corr_theo)
alpha <- 0.05
res <- BootRWCor(data,alpha,stat_test='empirical',Nboot=1000)
```

`BootRWCor_SD` *Booootstrap multiple testing method of Romano & Wolf (2005) for correlations, with stepdown procedure.*

Description

Multiple testing method based on the evaluation of quantile by bootstrap in the initial dataset (Romano & Wolf (2005)), with stepdown procedure.

Usage

```
BootRWCor_SD(data, alpha, stat_test = "empirical", Nboot = 1000,
  vect = FALSE)
```

Arguments

`data`	matrix of observations
`alpha`	level of multiple testing
`stat_test`	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1+corr)/(1-corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt(1-corr^2)$ **'gaussian'** $\sqrt{n}*mean(Y)/sd(Y)$ with $Y = (X_i - mean(X_i))(X_j - mean(X_j))$
`Nboot`	number of iterations for Bootstrap quantile evaluation
`vect`	if TRUE returns a vector of TRUE/FALSE values, corresponding to `vectorize(cor(data))`; if FALSE, returns an array containing rows and columns of significative correlations

Value

Returns

- a vector of logicals, equal to TRUE if the corresponding element of the statistic vector is rejected, if `vect=TRUE`,
- a vector containing indexes $\{(i,j),\ i<j\}$ for which correlation between variables i and j is significative, if `vect=FALSE`.

References

Romano, J. P., & Wolf, M. (2005). Exact and approximate stepdown methods for multiple hypothesis testing. Journal of the American Statistical Association, 100(469), 94-108.

Roux, M. (2018). Graph inference by multiple testing with application to Neuroimaging, Ph.D., Université Grenoble Alpes, France, https://tel.archives-ouvertes.fr/tel-01971574v1.

See Also

ApplyFwerCor, BootRWCor

Examples

```
n <- 100
p <- 10
corr_theo <- diag(1,p)
data <- MASS::mvrnorm(n,rep(0,p),corr_theo)
alpha <- 0.05
res <- BootRWCor_SD(data,alpha,stat_test='empirical',Nboot=1000)
```

covDcor *Returns the theoretical covariance of empirical correlations.*

Description

Returns the theoretical covariance of empirical correlations.

Usage

```
covDcor(r)
```

Arguments

r	a correlation matrix

Value

Returns the theoretical covariance of empirical correlations.

References

Aitkin, M. A. (1969). Some tests for correlation matrices. Biometrika, 443-446.

See Also

covDcorNorm

Examples

```
p <- 10
corr_theo <- diag(1,p)
corr_theo[2:p,] <- 0.3
corr_theo[,2:p] <- 0.3
covDcor(corr_theo)
```

covDcorNorm *Returns the theoretical covariance of test statistics for correlation testing.*

Description

Returns the theoretical covariance of test statistics for correlation testing.

Usage

```
covDcorNorm(cor_mat, stat_test = "empirical")
```

Arguments

cor_mat
: a correlation matrix

stat_test
: **'empirical'** $\sqrt{n} * abs(corr)$
'fisher' $\sqrt{n-3} * 1/2 * \log((1 + corr)/(1 - corr))$
'student' $\sqrt{n-2} * abs(corr)/\sqrt{(}1 - corr^2)$
Notice that 'gaussian' is not available.

Value

Returns the theoretical covariance of the test statistics.

See Also

covDcor, eval_stat

Examples

```
p <- 10
corr_theo <- diag(1,p)
corr_theo[2:p,] <- 0.3
corr_theo[,2:p] <- 0.3
covDcorNorm(corr_theo,stat_test='student')
```

---

eval_stat — *Evaluates the test statistics for tests on correlation matrix entries.*

Description

Evaluates the test statistics for tests on correlation matrix entries.

Usage

```
eval_stat(data, type = "empirical")
```

Arguments

data
: matrix of observations

type
: **'empirical'** $\sqrt{n} * abs(corr)$
'fisher' $\sqrt{n-3} * 1/2 * \log((1 + corr)/(1 - corr))$
'student' $\sqrt{n-2} * abs(corr)/\sqrt{(}1 - corr^2)$
'gaussian' $\sqrt{n} * mean(Y)/sd(Y)$ with $Y = (X_i - mean(X_i))(X_j - mean(X_j))$

Value

Returns the test statistics for correlation testing.

Examples

```
n <- 100
p <- 10
corr_theo <- diag(1,p)
data <- MASS::mvrnorm(n,rep(0,p),corr_theo)
stat <- eval_stat(data,'fisher')
```

`LCTboot` *Bootstrap procedure LCT-B proposed by Cai & Liu (2016) for correlation testing.*

Description

Bootstrap procedure LCT-B proposed by Cai & Liu (2016) for correlation testing.

Usage

```
LCTboot(data, alpha = 0.05, stat_test = "gaussian", Nboot = 100,
  vect = FALSE)
```

Arguments

`data`	matrix of observations
`alpha`	level of multiple testing
`stat_test`	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1+corr)/(1-corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt{(}1-corr^2)$ **'gaussian'** $\sqrt{n} * mean(Y)/sd(Y)$ with $Y = (X_i - mean(X_i))(X_j - mean(X_j))$
`Nboot`	number of iterations for bootstrap quantile evaluation
`vect`	if TRUE returns a vector of TRUE/FALSE values, corresponding to `vectorize(cor(data))`; if FALSE, returns an array containing rows and columns of significative correlations

Value

Returns

- a vector of logicals, equal to TRUE if the corresponding element of the statistic vector is rejected, if `vect=TRUE`,
- a vector containing indexes $\{(i, j),\ i < j\}$ for which correlation between variables i and j is significative, if `vect=FALSE`.

References

Cai, T. T., & Liu, W. (2016). Large-scale multiple testing of correlations. Journal of the American Statistical Association, 111(513), 229-240.

See Also

ApplyFdrCor, LCTNorm

Examples

```
n <- 100
p <- 10
corr_theo <- diag(1,p)
data <- MASS::mvrnorm(n,rep(0,p),corr_theo)
alpha <- 0.05
res <- LCTboot(data,alpha,stat_test='empirical',Nboot=100)
```

`LCTnorm` *Procedure LCT-N proposed by Cai & Liu (2016) for correlation testing.*

Description

Procedure LCT-N proposed by Cai & Liu (2016) for correlation testing.

Usage

```
LCTnorm(data, alpha = 0.05, stat_test = "gaussian", vect = FALSE)
```

Arguments

`data`	matrix of observations
`alpha`	level of multiple testing
`stat_test`	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1+corr)/(1-corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt{(1-corr^2)}$ **'gaussian'** $\sqrt{n} * mean(Y)/sd(Y)$ with $Y = (X_i - mean(X_i))(X_j - mean(X_j))$
`vect`	if TRUE returns a vector of TRUE/FALSE values, corresponding to `vectorize(cor(data))`; if FALSE, returns an array containing rows and columns of significative correlations

Value

Returns

- a vector of logicals, equal to TRUE if the corresponding element of the statistic vector is rejected, if `vect=TRUE`,
- a vector containing indexes $\{(i,j),\ i<j\}$ for which correlation between variables i and j is significative, if `vect=FALSE`.

References

Cai, T. T., & Liu, W. (2016). Large-scale multiple testing of correlations. Journal of the American Statistical Association, 111(513), 229-240.

See Also

ApplyFdrCor, LCTboot

Examples

```
n <- 100
p <- 10
corr_theo <- diag(1,p)
data <- MASS::mvrnorm(n,rep(0,p),corr_theo)
alpha <- 0.05
res <- LCTnorm(data,alpha,stat_test='empirical')
```

`maxTinftyCor` *Multiple testing method of Drton & Perlman (2007) for correlations.*

Description

Multiple testing method based on the evaluation of quantile by simulation of observations from the asymptotic distribution (Drton & Perlman (2007)).

Usage

```
maxTinftyCor(data, alpha = 0.05, stat_test = "empirical",
  Nboot = 1000, OmegaChap = covDcorNorm(cor(data), stat_test),
  vect = FALSE)
```

Arguments

`data`	matrix of observations
`alpha`	level of multiple testing
`stat_test`	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1+corr)/(1-corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt{(}1-corr^2)$ Notice that 'gaussian' is not available.
`Nboot`	number of iterations for Monte-Carlo quantile evaluation
`OmegaChap`	matrix of covariance of empirical correlations used for quantile evaluation; optional, useful for oracle estimation and step-down
`vect`	if TRUE returns a vector of TRUE/FALSE values, corresponding to `vectorize(cor(data))`; if FALSE, returns an array containing rows and columns of significative correlations

Value

Returns a vector of logicals, equal to TRUE if the corresponding element of stat is rejected.

References

Drton, M., & Perlman, M. D. (2007). Multiple testing and error control in Gaussian graphical model selection. Statistical Science, 22(3), 430-449.

Roux, M. (2018). Graph inference by multiple testing with application to Neuroimaging, Ph.D., Université Grenoble Alpes, France, https://tel.archives-ouvertes.fr/tel-01971574v1.

See Also

ApplyFwerCor, maxTinftyCor_SD

Examples

```
n <- 100
p <- 10
corr_theo <- diag(1,p)
data <- MASS::mvrnorm(n,rep(0,p),corr_theo)
alpha <- 0.05
res <- maxTinftyCor(data,alpha,stat_test='empirical',Nboot=1000)
```

`maxTinftyCor_SD` *Multiple testing method of Drton & Perlman (2007) for correlations, with stepdown procedure.*

Description

Multiple testing method based on the evaluation of quantile by simulation of observations from the asymptotic distribution (Drton & Perlman (2007)), with stepdown procedure.

Usage

```
maxTinftyCor_SD(data, alpha = 0.05, stat_test = "empirical",
  Nboot = 1000, OmegaChap = covDcorNorm(cor(data), stat_test),
  vect = FALSE)
```

Arguments

`data`	matrix of observations
`alpha`	level of multiple testing
`stat_test`	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1 + corr)/(1 - corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt{(}1 - corr^2)$ Notice that 'gaussian' is not available.

Nboot	number of iterations for Monte-Carlo quantile evaluation
OmegaChap	matrix of covariance of test statistics; optional, useful for oracle estimation and step-down
vect	if TRUE returns a vector of TRUE/FALSE values, corresponding to `vectorize(cor(data))`; if FALSE, returns an array containing rows and columns of significative correlations

Value

Returns

- a vector of logicals, equal to TRUE if the corresponding element of the statistic vector is rejected, if `vect=TRUE`,
- a vector containing indexes $\{(i,j),\, i<j\}$ for which correlation between variables i and j is significative, if `vect=FALSE`.

References

Drton, M., & Perlman, M. D. (2007). Multiple testing and error control in Gaussian graphical model selection. Statistical Science, 22(3), 430-449.

Roux, M. (2018). Graph inference by multiple testing with application to Neuroimaging, Ph.D., Université Grenoble Alpes, France, https://tel.archives-ouvertes.fr/tel-01971574v1.

See Also

ApplyFwerCor, maxTinftyCor

Examples

```
n <- 100
p <- 10
corr_theo <- diag(1,p)
data <- MASS::mvrnorm(n,rep(0,p),corr_theo)
alpha <- 0.05
res <- maxTinftyCor_SD(data,alpha,stat_test='empirical',Nboot=1000)
```

`SidakCor` *Sidak multiple testing procedure for correlations.*

Description

Sidak multiple testing procedure for correlations.

Usage

```
SidakCor(data, alpha = 0.05, stat_test = "empirical", vect = FALSE)
```

Arguments

data	matrix of observations
alpha	level of multiple testing
stat_test	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1+corr)/(1-corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt{(}1-corr^2)$ **'gaussian'** $\sqrt{n}*mean(Y)/sd(Y)$ with $Y=(X_i-mean(X_i))(X_j-mean(X_j))$
vect	if TRUE returns a vector of TRUE/FALSE values, corresponding to `vectorize(cor(data))`; if FALSE, returns an array containing rows and columns of significative correlations

Value

Returns

- a vector of logicals, equal to TRUE if the corresponding element of the statistic vector is rejected, if `vect=TRUE`,
- a vector containing indexes $\{(i,j),\ i<j\}$ for which correlation between variables i and j is significative, if `vect=FALSE`.

References

Roux, M. (2018). Graph inference by multiple testing with application to Neuroimaging, Ph.D., Université Grenoble Alpes, France, https://tel.archives-ouvertes.fr/tel-01971574v1.

Šidák, Z. (1967). Rectangular confidence regions for the means of multivariate normal distributions. Journal of the American Statistical Association, 62(318), 626-633.

See Also

ApplyFwerCor, SidakCor_SD

Examples

```
n <- 100
p <- 10
corr_theo <- diag(1,p)
data <- MASS::mvrnorm(n,rep(0,p),corr_theo)
corr_mat <- cor(data)
corr_vect <- corr_mat[upper.tri(corr_mat)]
alpha <- 0.05
res <- SidakCor(data,alpha,stat_test='empirical')
```

SidakCor_SD *Sidak multiple testing method for correlations with stepdown procedure.*

Description

Sidak multiple testing method for correlations with stepdown procedure.

Usage

```
SidakCor_SD(data, alpha, stat_test = "empirical", vect = FALSE)
```

Arguments

data	matrix of observations
alpha	level of multiple testing
stat_test	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1 + corr)/(1 - corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt{(}1 - corr^2)$ **'gaussian'** $\sqrt{n}*mean(Y)/sd(Y)$ with $Y = (X_i - mean(X_i))(X_j - mean(X_j))$
vect	if TRUE returns a vector of TRUE/FALSE values, corresponding to `vectorize(cor(data))`; if FALSE, returns an array containing rows and columns of significative correlations

Value

Returns

- a vector of logicals, equal to TRUE if the corresponding element of the statistic vector is rejected, if `vect=TRUE`,
- a vector containing indexes $\{(i, j),\ i < j\}$ for which correlation between variables i and j is significative, if `vect=FALSE`.

References

Roux, M. (2018). Graph inference by multiple testing with application to Neuroimaging, Ph.D., Université Grenoble Alpes, France, https://tel.archives-ouvertes.fr/tel-01971574v1.

Šidák, Z. (1967). Rectangular confidence regions for the means of multivariate normal distributions. Journal of the American Statistical Association, 62(318), 626-633.

See Also

ApplyFwerCor, SidakCor

Examples

```
n <- 100
p <- 10
corr_theo <- diag(1,p)
data <- MASS::mvrnorm(n,rep(0,p),corr_theo)
alpha <- 0.05
res <- SidakCor_SD(data,alpha,stat_test='empirical')
```

`SimuFdr` *Simulates Gaussian data with a given correlation matrix and applies a FDR controlling procedure on the correlations.*

Description

Simulates Gaussian data with a given correlation matrix and applies a FDR controlling procedure on the correlations.

Usage

```
SimuFdr(corr_theo, n = 100, Nsimu = 1, alpha = 0.05,
  stat_test = "empirical", method = "LCTnorm", Nboot = 1000,
  seed = NULL)
```

Arguments

`corr_theo`	the correlation matrix of Gaussien data simulated
`n`	sample size
`Nsimu`	number of simulations
`alpha`	level of multiple testing
`stat_test`	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1+corr)/(1-corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt(1-corr^2)$ **'gaussian'** $\sqrt{n} * mean(Y)/sd(Y)$ with $Y = (X_i - mean(X_i))(X_j - mean(X_j))$
`method`	choice between 'LCTnorm' and 'LCTboot', developped by Cai & Liu (2016), 'BH', traditional Benjamini-Hochberg (1995)'s procedure, and 'BHboot', Benjamini-Hochberg (1995)'s procedure with bootstrap evaluation of pvalues
`Nboot`	number of iterations for Monte-Carlo of bootstrap quantile evaluation
`seed`	seed for the Gaussian simulations

Value

Returns a line vector containing estimated fwer, estimated fdr, estimated power, estimated true discovery rate.

References

Benjamini, Y., & Hochberg, Y. (1995). Controlling the false discovery rate: a practical and powerful approach to multiple testing. Journal of the royal statistical society. Series B (Methodological), 289-300.

Cai, T. T., & Liu, W. (2016). Large-scale multiple testing of correlations. Journal of the American Statistical Association, 111(513), 229-240.

Roux, M. (2018). Graph inference by multiple testing with application to Neuroimaging, Ph.D., Université Grenoble Alpes, France, https://tel.archives-ouvertes.fr/tel-01971574v1.

See Also

ApplyFdrCor, SimuFwer

Examples

```
Nsimu <- 1000
n <- 100
p <- 10
corr_theo <- diag(1,p)
alpha <- 0.05
res <- SimuFdr(corr_theo,n,Nsimu,alpha,stat_test='empirical',method='LCTnorm')
```

`SimuFwer` *Simulates Gaussian data with a given correlation matrix and applies a FWER controlling procedure on the correlations.*

Description

Simulates Gaussian data with a given correlation matrix and applies a FWER controlling procedure on the correlations.

Usage

```
SimuFwer(corr_theo, n = 100, Nsimu = 1, alpha = 0.05,
  stat_test = "empirical", method = "MaxTinfty", Nboot = 1000,
  stepdown = TRUE, seed = NULL)
```

Arguments

`corr_theo`	the correlation matrix of Gaussien data simulated
`n`	sample size
`Nsimu`	number of simulations
`alpha`	level of multiple testing
`stat_test`	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1 + corr)/(1 - corr))$

	'student' $\sqrt{n-2} * abs(corr)/\sqrt(1 - corr^2)$
	'gaussian' $\sqrt{n} * mean(Y)/sd(Y)$ with $Y = (X_i - mean(X_i))(X_j - mean(X_j))$
`method`	choice between 'Bonferroni', 'Sidak', 'BootRW', 'MaxTinfty'
`Nboot`	number of iterations for Monte-Carlo of bootstrap quantile evaluation
`stepdown`	logical, if TRUE a stepdown procedure is applied
`seed`	seed for the Gaussian simulations

Value

Returns a line vector containing estimated fwer, estimated fdr, estimated power, estimated true discovery rate.

References

Bonferroni, C. E. (1935). Il calcolo delle assicurazioni su gruppi di teste. Studi in onore del professore salvatore ortu carboni, 13-60.

Drton, M., & Perlman, M. D. (2007). Multiple testing and error control in Gaussian graphical model selection. Statistical Science, 22(3), 430-449.

Romano, J. P., & Wolf, M. (2005). Exact and approximate stepdown methods for multiple hypothesis testing. Journal of the American Statistical Association, 100(469), 94-108.

Roux, M. (2018). Graph inference by multiple testing with application to Neuroimaging, Ph.D., Université Grenoble Alpes, France, https://tel.archives-ouvertes.fr/tel-01971574v1.

Westfall, P.H. & Young, S. (1993) Resampling-based multiple testing: Examples and methods for p-value adjustment, John Wiley & Sons, vol. 279.

See Also

ApplyFwerCor, SimuFwer_oracle, SimuFdr

Examples

```
Nsimu <- 1000
n <- 100
p <- 10
corr_theo <- diag(1,p)
alpha <- 0.05
res <- SimuFwer(corr_theo,n,Nsimu,alpha,stat_test='empirical',method='Bonferroni',stepdown=FALSE)
```

SimuFwer_oracle — *Simulates Gaussian data with a given correlation matrix and applies oracle MaxTinfty on the correlations.*

Description

Simulates Gaussian data with a given correlation matrix and applies oracle MaxTinfty (i.e. Drton & Perlman (2007)'s procedure with the true correlation matrix) on the correlations.

Usage

```
SimuFwer_oracle(corr_theo, n = 100, Nsimu = 1, alpha = 0.05,
  stat_test = "empirical", method = "MaxTinfty", Nboot = 1000,
  stepdown = TRUE, seed = NULL)
```

Arguments

`corr_theo`	the correlation matrix of Gaussien data simulated
`n`	sample size
`Nsimu`	number of simulations
`alpha`	level of multiple testing
`stat_test`	**'empirical'** $\sqrt{n} * abs(corr)$ **'fisher'** $\sqrt{n-3} * 1/2 * \log((1+corr)/(1-corr))$ **'student'** $\sqrt{n-2} * abs(corr)/\sqrt{(}1-corr^2)$ **'gaussian'** $\sqrt{n}*mean(Y)/sd(Y)$ with $Y=(X_i-mean(X_i))(X_j-mean(X_j))$
`method`	only 'MaxTinfty' available
`Nboot`	number of iterations for Monte-Carlo of bootstrap quantile evaluation
`stepdown`	logical, if TRUE a stepdown procedure is applied
`seed`	seed for the Gaussian simulations

Value

Returns a line vector containing estimated fwer, estimated fdr, estimated power, estimated true discovery rate.

References

Drton, M., & Perlman, M. D. (2007). Multiple testing and error control in Gaussian graphical model selection. Statistical Science, 22(3), 430-449.

Roux, M. (2018). Graph inference by multiple testing with application to Neuroimaging, Ph.D., Université Grenoble Alpes, France, https://tel.archives-ouvertes.fr/tel-01971574v1.

See Also

ApplyFwerCor_Oracle, SimuFwer

Examples

```
Nsimu <- 1000
n <- 50
p <- 10
corr_theo <- diag(1,p)
alpha <- 0.05
res <- SimuFwer_oracle(corr_theo,n,Nsimu,alpha,stat_test='empirical',stepdown=FALSE,Nboot=100)
```

`vectorize` *Returns a vector containing the upper triangle of a matrix, without the diagonal.*

Description

Returns a vector containing the upper triangle of a matrix, without the diagonal.

Usage

```
vectorize(mat)
```

Arguments

`mat`	a square matrix

Value

Returns a vector containing the upper triangle of a matrix, without the diagonal.

Examples

```
vectorize(matrix(1:9,3,3))
```

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