# Package 'cTMed'

January 19, 2025				
Title Continuous Time Mediation				
Version 1.0.5				
<b>Description</b> Calculates standard errors and confidence intervals for effects in continuous-time mediation models. This package extends the work of Deboeck and Preacher (2015) <doi:10.1080 10705511.2014.973960=""> and Ryan and Hamaker (2021) <doi:10.1007 s11336-021-09767-0=""> by providing methods to generate standard errors and confidence intervals for the total, direct, and indirect effects in these models.</doi:10.1007></doi:10.1080>				
<pre>URL https://github.com/jeksterslab/cTMed,</pre>				
https://jeksterslab.github.io/cTMed/				
<pre>BugReports https://github.com/jeksterslab/cTMed/issues License GPL (&gt;= 3)</pre>				
Encoding UTF-8				
<b>Roxygen</b> list(markdown = TRUE)				
<b>Depends</b> R (>= $3.5.0$ )				
LinkingTo Rcpp, RcppArmadillo				
Imports Rcpp, numDeriv, parallel, simStateSpace				
Suggests knitr, rmarkdown, testthat, expm, bootStateSpace				
Remotes jeksterslab/bootStateSpace				
RoxygenNote 7.3.2				
NeedsCompilation yes				
Author Ivan Jacob Agaloos Pesigan [aut, cre, cph] ( <a href="https://orcid.org/0000-0003-4818-8420">https://orcid.org/0000-0003-4818-8420</a> )				
Maintainer Ivan Jacob Agaloos Pesigan <r.jeksterslab@gmail.com></r.jeksterslab@gmail.com>				
Contents				
BootBeta				

2 Contents

BootIndirectCentral	
BootMed	
BootMedStd	 . 18
BootTotalCentral	 . 22
confint.ctmedboot	 . 26
confint.ctmeddelta	 . 29
confint.ctmedmc	 . 31
DeltaBeta	 . 33
DeltaBetaStd	 . 36
DeltaIndirectCentral	 . 40
DeltaMed	 . 43
DeltaMedStd	 . 47
DeltaTotalCentral	 . 51
Direct	
DirectStd	
ExpCov	
ExpMean	
Indirect	
IndirectCentral	
IndirectStd	
MCBeta	. 69
MCBetaStd	. 72
MCIndirectCentral	. 72
MCMed	. 80
MCMedStd	
MCPhi	
MCT-talCourtel	
MCTotalCentral	
Med	
MedStd	
plot.ctmedboot	
plot.ctmeddelta	
plot.ctmedmc	
plot.ctmedmed	
plot.ctmedtraj	. 107
PosteriorBeta	. 108
PosteriorIndirectCentral	
PosteriorMed	
PosteriorTotalCentral	
print.ctmedboot	
print.ctmeddelta	
print.ctmedeffect	
print.ctmedmc	 . 126
print.ctmedmcphi	 . 128
print.ctmedmed	 . 129
print.ctmedtraj	 . 130
summary.ctmedboot	 . 131
summary.ctmeddelta	

Boot	Beta	Bootstro Lagged Interval	Сов		_									
													 	14)
Index														149
	Trajectory			 	•	 •	 							 146
	TotalStd													
	TotalCentral			 			 				 			 142
	Total			 			 				 			 140
	summary.ctmedtraj	j		 			 				 			 139
	summary.ctmedpos	steriorphi.		 			 				 			 139
	summary.ctmedme	d		 			 				 			 137
	summary.ctmedmc	:		 			 				 			 136

# Description

This function generates a bootstrap method sampling distribution for the elements of the matrix of lagged coefficients  $\boldsymbol{\beta}$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model drift matrix  $\boldsymbol{\Phi}$ .

# Usage

```
BootBeta(phi, phi_hat, delta_t, ncores = NULL, tol = 0.01)
```

# **Arguments**

phi	List of numeric matrices. Each element of the list is a bootstrap estimate of the drift matrix $(\Phi)$ .
phi_hat	Numeric matrix. The estimated drift matrix $(\hat{\Phi})$ from the original data set. phi_hat should have row and column names pertaining to the variables in the system.
delta_t	Numeric. Time interval $(\Delta t)$ .
ncores	Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.
tol	Numeric. Smallest possible time interval to allow.

## **Details**

See Total().

#### Value

Returns an object of class ctmedboot which is a list with the following elements:

```
call Function call.args Function arguments.fun Function used ("BootBeta").output A list with length of length(delta_t).
```

Each element in the output list has the following elements:

est Estimated elements of the matrix of lagged coefficients.

thetahatstar A matrix of bootstrap elements of the matrix of lagged coefficients.

#### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

Other Continuous Time Mediation Functions: BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
## Not run:
library(bootStateSpace)
# prepare parameters
## number of individuals
n <- 50
## time points
time <- 100
delta_t <- 0.10
## dynamic structure
p <- 3</pre>
```

```
mu0 < -rep(x = 0, times = p)
sigma0 <- matrix(</pre>
  data = c(
    1.0,
    0.2,
    0.2,
    0.2,
    1.0,
    0.2,
    0.2,
    0.2,
    1.0
  ),
  nrow = p
)
sigma0_1 \leftarrow t(chol(sigma0))
mu \leftarrow rep(x = 0, times = p)
phi <- matrix(</pre>
  data = c(
    -0.357,
    0.771,
    -0.450,
    0.0,
    -0.511,
    0.729,
    0,
    0,
    -0.693
  ),
  nrow = p
)
sigma <- matrix(</pre>
  data = c(
    0.24455556,
    0.02201587,
    -0.05004762,
    0.02201587,
    0.07067800,
    0.01539456,
    -0.05004762,
    0.01539456,
    0.07553061
  ),
  nrow = p
)
sigma_l <- t(chol(sigma))</pre>
## measurement model
k <- 3
nu \leftarrow rep(x = 0, times = k)
lambda <- diag(k)</pre>
theta <- 0.2 * diag(k)
theta_l <- t(chol(theta))</pre>
```

```
boot <- PBSSMOUFixed(</pre>
 R = 10L, # use at least 1000 in actual research
 path = getwd(),
 prefix = "ou",
 n = n,
 time = time,
 delta_t = delta_t,
 mu0 = mu0,
 sigma0_1 = sigma0_1,
 mu = mu,
 phi = phi,
 sigma_l = sigma_l,
 nu = nu,
 lambda = lambda,
 theta_l = theta_l,
 ncores = NULL, # consider using multiple cores
 seed = 42
)
phi_hat <- phi
colnames(phi_hat) <- rownames(phi_hat) <- c("x", "m", "y")</pre>
phi <- extract(object = boot, what = "phi")</pre>
# Specific time interval ------
BootBeta(
 phi = phi,
 phi_hat = phi_hat,
 delta_t = 1
)
# Range of time intervals ------
boot <- BootBeta(</pre>
 phi = phi,
 phi_hat = phi_hat,
 delta_t = 1:5
plot(boot)
plot(boot, type = "bc") # bias-corrected
# Methods -----
# BootBeta has a number of methods including
# print, summary, confint, and plot
print(boot)
summary(boot)
confint(boot, level = 0.95)
print(boot, type = "bc") # bias-corrected
summary(boot, type = "bc")
confint(boot, level = 0.95, type = "bc")
## End(Not run)
```

BootBetaStd 7

BootBetaStd	Bootstrap Sampling Distribution for the Elements of the Standardized Matrix of Lagged Coefficients Over a Specific Time Interval or a Range of Time Intervals
	·

#### **Description**

This function generates a bootstrap method sampling distribution for the elements of the standardized matrix of lagged coefficients  $\beta$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model drift matrix  $\Phi$ .

## Usage

```
BootBetaStd(phi, sigma, phi_hat, sigma_hat, delta_t, ncores = NULL, tol = 0.01)
```

## Arguments

phi	List of numeric matrices. Each element of the list is a bootstrap estimate of the drift matrix $(\Phi)$ .
sigma	List of numeric matrices. Each element of the list is a bootstrap estimate of the process noise covariance matrix $(\Sigma)$ .
phi_hat	Numeric matrix. The estimated drift matrix $(\hat{\Phi})$ from the original data set. phi_hat should have row and column names pertaining to the variables in the system.
sigma_hat	Numeric matrix. The estimated process noise covariance matrix $(\hat{\Sigma})$ from the original data set.
delta_t	Numeric. Time interval ( $\Delta t$ ).
ncores	Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.
tol	Numeric. Smallest possible time interval to allow.

#### **Details**

See TotalStd().

#### Value

Returns an object of class ctmedboot which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("BootBetaStd").

output A list with length of length(delta\_t).

Each element in the output list has the following elements:

est Estimated elements of the standardized matrix of lagged coefficients.

thetahatstar A matrix of bootstrap elements of the standardized matrix of lagged coefficients.

8 BootBetaStd

#### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
## Not run:
library(bootStateSpace)
# prepare parameters
## number of individuals
n <- 50
## time points
time <- 100
delta_t <- 0.10
## dynamic structure
p <- 3
mu0 < -rep(x = 0, times = p)
sigma0 <- matrix(</pre>
  data = c(
    1.0,
    0.2,
    0.2,
    0.2,
    1.0,
    0.2,
    0.2,
    0.2,
    1.0
  ),
  nrow = p
)
```

BootBetaStd 9

```
sigma0_1 \leftarrow t(chol(sigma0))
mu \leftarrow rep(x = 0, times = p)
phi <- matrix(</pre>
  data = c(
    -0.357,
    0.771,
    -0.450,
    0.0,
    -0.511,
    0.729,
    0,
    0,
    -0.693
  ),
  nrow = p
)
sigma <- matrix(</pre>
  data = c(
    0.24455556,
    0.02201587,
    -0.05004762,
    0.02201587,
    0.07067800,
    0.01539456,
    -0.05004762,
    0.01539456,
    0.07553061
  ),
  nrow = p
sigma_l <- t(chol(sigma))</pre>
## measurement model
k <- 3
nu \leftarrow rep(x = 0, times = k)
lambda <- diag(k)</pre>
theta <- 0.2 * diag(k)
theta_l \leftarrow t(chol(theta))
boot <- PBSSMOUFixed(</pre>
  R = 10L, # use at least 1000 in actual research
  path = getwd(),
  prefix = "ou",
  n = n,
  time = time,
  delta_t = delta_t,
  mu0 = mu0,
  sigma0_1 = sigma0_1,
  mu = mu,
  phi = phi,
  sigma_l = sigma_l,
  nu = nu,
  lambda = lambda,
  theta_1 = theta_1,
```

```
ncores = NULL, # consider using multiple cores
)
phi_hat <- phi
colnames(phi_hat) \leftarrow rownames(phi_hat) \leftarrow c("x", "m", "y")
sigma_hat <- sigma</pre>
phi <- extract(object = boot, what = "phi")</pre>
sigma <- extract(object = boot, what = "sigma")</pre>
# Specific time interval ------
BootBetaStd(
 phi = phi,
 sigma = sigma,
 phi_hat = phi_hat,
 sigma_hat = sigma_hat,
 delta_t = 1
)
# Range of time intervals ------
boot <- BootBetaStd(</pre>
 phi = phi,
 sigma = sigma,
 phi_hat = phi_hat,
 sigma_hat = sigma_hat,
 delta_t = 1:5
plot(boot)
plot(boot, type = "bc") # bias-corrected
# Methods ------
# BootBetaStd has a number of methods including
# print, summary, confint, and plot
print(boot)
summary(boot)
confint(boot, level = 0.95)
print(boot, type = "bc") # bias-corrected
summary(boot, type = "bc")
confint(boot, level = 0.95, type = "bc")
## End(Not run)
```

 ${\tt BootIndirectCentral}$ 

Bootstrap Sampling Distribution for the Indirect Effect Centrality Over a Specific Time Interval or a Range of Time Intervals

## **Description**

This function generates a bootstrap method sampling distribution for the indirect effect centrality over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model drift matrix  $\Phi$ .

#### Usage

BootIndirectCentral(phi, phi\_hat, delta\_t, ncores = NULL, tol = 0.01)

## **Arguments**

phi	List of numeric matrices. Each element of the list is a bootstrap estimate of the drift matrix $(\Phi)$ .
phi_hat	Numeric matrix. The estimated drift matrix $(\hat{\Phi})$ from the original data set. phi_hat should have row and column names pertaining to the variables in the system.
delta_t	Numeric. Time interval ( $\Delta t$ ).
ncores	Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.
tol	Numeric. Smallest possible time interval to allow.

#### **Details**

See IndirectCentral() more details.

#### Value

Returns an object of class ctmedboot which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("BootIndirectCentral").

output A list with length of length(delta\_t).

Each element in the output list has the following elements:

est A vector of indirect effect centrality.

thetahatstar A matrix of bootstrap indirect effect centrality.

## Author(s)

Ivan Jacob Agaloos Pesigan

## References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootMed(), BootMed(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
## Not run:
library(bootStateSpace)
# prepare parameters
## number of individuals
n <- 50
## time points
time <- 100
delta_t <- 0.10
## dynamic structure
p <- 3
mu0 < -rep(x = 0, times = p)
sigma0 <- matrix(</pre>
  data = c(
    1.0,
    0.2,
    0.2,
    0.2,
    1.0,
    0.2,
    0.2,
    0.2,
    1.0
  ),
  nrow = p
)
sigma0_1 \leftarrow t(chol(sigma0))
mu \leftarrow rep(x = 0, times = p)
phi <- matrix(</pre>
  data = c(
    -0.357,
    0.771,
    -0.450,
    0.0,
    -0.511,
    0.729,
    0,
    0,
    -0.693
  ),
  nrow = p
```

```
sigma <- matrix(</pre>
 data = c(
   0.24455556,
   0.02201587,
   -0.05004762,
   0.02201587,
   0.07067800,
   0.01539456,
   -0.05004762,
   0.01539456,
   0.07553061
 ),
 nrow = p
)
sigma_l <- t(chol(sigma))</pre>
## measurement model
k <- 3
nu \leftarrow rep(x = 0, times = k)
lambda <- diag(k)</pre>
theta <- 0.2 * diag(k)
theta_l <- t(chol(theta))</pre>
boot <- PBSSMOUFixed(</pre>
 R = 10L, # use at least 1000 in actual research
 path = getwd(),
 prefix = "ou",
 n = n,
 time = time,
 delta_t = delta_t,
 mu0 = mu0,
 sigma0_1 = sigma0_1,
 mu = mu,
 phi = phi,
 sigma_l = sigma_l,
 nu = nu,
 lambda = lambda,
 theta_l = theta_l,
 ncores = NULL, # consider using multiple cores
 seed = 42
)
phi_hat <- phi
colnames(phi_hat) \leftarrow rownames(phi_hat) \leftarrow c("x", "m", "y")
phi <- extract(object = boot, what = "phi")</pre>
# Specific time interval ------
BootIndirectCentral(
 phi = phi,
 phi_hat = phi_hat,
 delta_t = 1
)
# Range of time intervals ------
```

14 BootMed

```
boot <- BootIndirectCentral(</pre>
  phi = phi,
  phi_hat = phi_hat,
  delta_t = 1:5
)
plot(boot)
plot(boot, type = "bc") # bias-corrected
# BootIndirectCentral has a number of methods including
# print, summary, confint, and plot
print(boot)
summary(boot)
confint(boot, level = 0.95)
print(boot, type = "bc") # bias-corrected
summary(boot, type = "bc")
confint(boot, level = 0.95, type = "bc")
## End(Not run)
```

BootMed

Bootstrap Sampling Distribution of Total, Direct, and Indirect Effects of X on Y Through M Over a Specific Time Interval or a Range of Time Intervals

# Description

This function generates a bootstrap method sampling distribution of the total, direct and indirect effects of the independent variable X on the dependent variable Y through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model drift matrix  $\mathbf{\Phi}$ .

## Usage

```
BootMed(phi, phi_hat, delta_t, from, to, med, ncores = NULL, tol = 0.01)
```

#### **Arguments**

phi	List of numeric matrices. Each element of the list is a bootstrap estimate of the drift matrix $(\Phi)$ .
phi_hat	Numeric matrix. The estimated drift matrix $(\hat{\Phi})$ from the original data set. phi_hat should have row and column names pertaining to the variables in the system.
delta_t	Numeric. Time interval ( $\Delta t$ ).
from	Character string. Name of the independent variable $X$ in phi.
to	Character string. Name of the dependent variable $Y$ in phi.

BootMed 15

med Character vector. Name/s of the mediator variable/s in phi.

ncores Positive integer. Number of cores to use. If ncores = NULL, use a single core.

Consider using multiple cores when number of replications R is a large value.

tol Numeric. Smallest possible time interval to allow.

#### **Details**

See Total(), Direct(), and Indirect() for more details.

#### Value

Returns an object of class ctmedboot which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("BootMed").

output A list with length of length(delta\_t).

Each element in the output list has the following elements:

est A vector of total, direct, and indirect effects.

thetahatstar A matrix of bootstrap total, direct, and indirect effects.

#### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

BootMed BootMed

```
## Not run:
library(bootStateSpace)
# prepare parameters
## number of individuals
n <- 50
## time points
time <- 100
delta_t <- 0.10
## dynamic structure
p <- 3
mu0 < -rep(x = 0, times = p)
sigma0 <- matrix(</pre>
  data = c(
    1.0,
    0.2,
    0.2,
    0.2,
    1.0,
    0.2,
    0.2,
    0.2,
    1.0
  ),
  nrow = p
)
sigma0_l <- t(chol(sigma0))</pre>
mu \leftarrow rep(x = 0, times = p)
phi <- matrix(</pre>
  data = c(
    -0.357,
    0.771,
    -0.450,
    0.0,
    -0.511,
    0.729,
    0,
    0,
    -0.693
  ),
  nrow = p
)
sigma <- matrix(</pre>
  data = c(
    0.24455556,
    0.02201587,
    -0.05004762,
    0.02201587,
    0.07067800,
    0.01539456,
    -0.05004762,
    0.01539456,
```

BootMed 17

```
0.07553061
 ),
 nrow = p
)
sigma_l <- t(chol(sigma))</pre>
## measurement model
k <- 3
nu \leftarrow rep(x = 0, times = k)
lambda <- diag(k)</pre>
theta <- 0.2 * diag(k)
theta_l <- t(chol(theta))</pre>
boot <- PBSSMOUFixed(</pre>
 R = 10L, # use at least 1000 in actual research
 path = getwd(),
 prefix = "ou",
 n = n,
 time = time,
 delta_t = delta_t,
 mu0 = mu0,
 sigma0_1 = sigma0_1,
 mu = mu,
 phi = phi,
 sigma_l = sigma_l,
 nu = nu,
 lambda = lambda,
 theta_l = theta_l,
 ncores = NULL, # consider using multiple cores
 seed = 42
)
phi_hat <- phi</pre>
colnames(phi_hat) <- rownames(phi_hat) <- c("x", "m", "y")</pre>
phi <- extract(object = boot, what = "phi")</pre>
# Specific time interval ------
BootMed(
 phi = phi,
 phi_hat = phi_hat,
 delta_t = 1,
 from = "x",
 to = "y",
 med = "m"
)
# Range of time intervals ------
boot <- BootMed(</pre>
 phi = phi,
 phi_hat = phi_hat,
 delta_t = 1:5,
 from = "x",
 to = "y",
 med = "m"
```

BootMedStd

Bootstrap Sampling Distribution of Standardized Total, Direct, and Indirect Effects of X on Y Through M Over a Specific Time Interval or a Range of Time Intervals

## **Description**

This function generates a bootstrap method sampling distribution of the standardized total, direct and indirect effects of the independent variable X on the dependent variable Y through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model drift matrix  $\mathbf{\Phi}$ .

# Usage

```
BootMedStd(
   phi,
   sigma,
   phi_hat,
   sigma_hat,
   delta_t,
   from,
   to,
   med,
   ncores = NULL,
   tol = 0.01
)
```

#### Arguments

phi

List of numeric matrices. Each element of the list is a bootstrap estimate of the drift matrix  $(\Phi)$ .

sigma	List of numeric matrices. Each element of the list is a bootstrap estimate of the process noise covariance matrix $(\Sigma)$ .
phi_hat	Numeric matrix. The estimated drift matrix $(\hat{\Phi})$ from the original data set. phi_hat should have row and column names pertaining to the variables in the system.
sigma_hat	Numeric matrix. The estimated process noise covariance matrix $(\hat{\Sigma})$ from the original data set.
delta_t	Numeric. Time interval ( $\Delta t$ ).
from	Character string. Name of the independent variable $X$ in phi.
to	Character string. Name of the dependent variable $Y$ in phi.
med	Character vector. Name/s of the mediator variable/s in phi.
ncores	Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.
tol	Numeric. Smallest possible time interval to allow.

#### **Details**

See TotalStd(), DirectStd(), and IndirectStd() for more details.

#### Value

Returns an object of class ctmedboot which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("BootMedStd").

output A list with length of length(delta\_t).

Each element in the output list has the following elements:

est A vector of standardized total, direct, and indirect effects.

**thetahatstar** A matrix of bootstrap standardized total, direct, and indirect effects.

# Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
## Not run:
library(bootStateSpace)
# prepare parameters
## number of individuals
n <- 50
## time points
time <- 100
delta_t <- 0.10
## dynamic structure
p <- 3
mu0 < -rep(x = 0, times = p)
sigma0 <- matrix(</pre>
  data = c(
    1.0,
    0.2,
    0.2,
    0.2,
    1.0,
    0.2,
    0.2,
    0.2,
    1.0
  ),
  nrow = p
)
sigma0_l <- t(chol(sigma0))</pre>
mu \leftarrow rep(x = 0, times = p)
phi <- matrix(</pre>
  data = c(
    -0.357,
    0.771,
    -0.450,
    0.0,
    -0.511,
    0.729,
    0,
    0,
    -0.693
  ),
  nrow = p
```

```
sigma <- matrix(</pre>
 data = c(
   0.24455556,
    0.02201587,
    -0.05004762,
    0.02201587,
    0.07067800,
    0.01539456,
    -0.05004762,
    0.01539456,
    0.07553061
  ),
  nrow = p
)
sigma_l <- t(chol(sigma))</pre>
## measurement model
k <- 3
nu \leftarrow rep(x = 0, times = k)
lambda <- diag(k)</pre>
theta <- 0.2 * diag(k)
theta_l <- t(chol(theta))</pre>
boot <- PBSSMOUFixed(</pre>
  R = 10L, # use at least 1000 in actual research
  path = getwd(),
  prefix = "ou",
  n = n,
  time = time,
  delta_t = delta_t,
  mu0 = mu0,
  sigma0_1 = sigma0_1,
  mu = mu,
  phi = phi,
  sigma_l = sigma_l,
  nu = nu,
  lambda = lambda,
  theta_l = theta_l,
  ncores = NULL, # consider using multiple cores
  seed = 42
)
phi_hat <- phi
colnames(phi_hat) \leftarrow rownames(phi_hat) \leftarrow c("x", "m", "y")
sigma_hat <- sigma</pre>
phi <- extract(object = boot, what = "phi")</pre>
sigma <- extract(object = boot, what = "sigma")</pre>
# Specific time interval ------
BootMedStd(
  phi = phi,
  sigma = sigma,
  phi_hat = phi_hat,
  sigma_hat = sigma_hat,
```

```
delta_t = 1,
 from = "x",
 to = "y",
 med = "m"
)
# Range of time intervals ------
boot <- BootMedStd(</pre>
 phi = phi,
 sigma = sigma,
 phi_hat = phi_hat,
 sigma_hat = sigma_hat,
 delta_t = 1:5,
 from = "x",
 to = "y",
 med = "m"
)
plot(boot)
plot(boot, type = "bc") # bias-corrected
# Methods ------
# BootMedStd has a number of methods including
# print, summary, confint, and plot
print(boot)
summary(boot)
confint(boot, level = 0.95)
print(boot, type = "bc") # bias-corrected
summary(boot, type = "bc")
confint(boot, level = 0.95, type = "bc")
## End(Not run)
```

BootTotalCentral

Bootstrap Sampling Distribution for the Total Effect Centrality Over a Specific Time Interval or a Range of Time Intervals

# Description

This function generates a bootstrap method sampling distribution for the total effect centrality over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model drift matrix  $\Phi$ .

## Usage

```
BootTotalCentral(phi, phi_hat, delta_t, ncores = NULL, tol = 0.01)
```

## Arguments

phi	List of numeric matrices. Each element of the list is a bootstrap estimate of the drift matrix $(\Phi)$ .
phi_hat	Numeric matrix. The estimated drift matrix $(\hat{\Phi})$ from the original data set. phi_hat should have row and column names pertaining to the variables in the system.
delta_t	Numeric. Time interval ( $\Delta t$ ).
ncores	Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.
tol	Numeric. Smallest possible time interval to allow.

#### **Details**

See TotalCentral() more details.

#### Value

Returns an object of class ctmedboot which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("BootTotalCentral").

output A list with length of length(delta\_t).

Each element in the output list has the following elements:

est A vector of total effect centrality.

thetahatstar A matrix of bootstrap total effect centrality.

# Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
## Not run:
library(bootStateSpace)
# prepare parameters
## number of individuals
n <- 50
## time points
time <- 100
delta_t <- 0.10
## dynamic structure
p <- 3
mu0 < -rep(x = 0, times = p)
sigma0 <- matrix(</pre>
  data = c(
    1.0,
    0.2,
    0.2,
    0.2,
    1.0,
    0.2,
    0.2,
    0.2,
    1.0
  ),
  nrow = p
)
sigma0_l <- t(chol(sigma0))</pre>
mu \leftarrow rep(x = 0, times = p)
phi <- matrix(</pre>
  data = c(
    -0.357,
    0.771,
    -0.450,
    0.0,
    -0.511,
    0.729,
    0,
    0,
    -0.693
  ),
  nrow = p
```

```
sigma <- matrix(</pre>
 data = c(
   0.24455556,
   0.02201587,
   -0.05004762,
   0.02201587,
   0.07067800,
   0.01539456,
   -0.05004762,
   0.01539456,
   0.07553061
 ),
 nrow = p
)
sigma_l <- t(chol(sigma))</pre>
## measurement model
k <- 3
nu \leftarrow rep(x = 0, times = k)
lambda <- diag(k)</pre>
theta <- 0.2 * diag(k)
theta_l <- t(chol(theta))</pre>
boot <- PBSSMOUFixed(</pre>
 R = 10L, # use at least 1000 in actual research
 path = getwd(),
 prefix = "ou",
 n = n,
 time = time,
 delta_t = delta_t,
 mu0 = mu0,
 sigma0_1 = sigma0_1,
 mu = mu,
 phi = phi,
 sigma_l = sigma_l,
 nu = nu,
 lambda = lambda,
 theta_l = theta_l,
 ncores = NULL, # consider using multiple cores
 seed = 42
)
phi_hat <- phi
colnames(phi_hat) \leftarrow rownames(phi_hat) \leftarrow c("x", "m", "y")
phi <- extract(object = boot, what = "phi")</pre>
# Specific time interval ------
BootTotalCentral(
 phi = phi,
 phi_hat = phi_hat,
 delta_t = 1
)
# Range of time intervals ------
```

26 confint.ctmedboot

```
boot <- BootTotalCentral(</pre>
  phi = phi,
  phi_hat = phi_hat,
  delta_t = 1:5
)
plot(boot)
plot(boot, type = "bc") # bias-corrected
# BootTotalCentral has a number of methods including
# print, summary, confint, and plot
print(boot)
summary(boot)
confint(boot, level = 0.95)
print(boot, type = "bc") # bias-corrected
summary(boot, type = "bc")
confint(boot, level = 0.95, type = "bc")
## End(Not run)
```

confint.ctmedboot

Bootstrap Method Confidence Intervals

## **Description**

**Bootstrap Method Confidence Intervals** 

## Usage

```
## S3 method for class 'ctmedboot'
confint(object, parm = NULL, level = 0.95, type = "pc", ...)
```

## **Arguments**

object Object of class ctmedboot.

parm a specification of which parameters are to be given confidence intervals, either

a vector of numbers or a vector of names. If missing, all parameters are consid-

ered.

level the confidence level required.

type Charater string. Confidence interval type, that is, type = "pc" for percentile;

type = "bc" for bias corrected.

... additional arguments.

#### Value

Returns a data frame of confidence intervals.

confint.ctmedboot 27

## Author(s)

Ivan Jacob Agaloos Pesigan

```
## Not run:
library(bootStateSpace)
# prepare parameters
## number of individuals
n <- 50
## time points
time <- 100
delta_t <- 0.10
## dynamic structure
p <- 3
mu0 < -rep(x = 0, times = p)
sigma0 <- matrix(</pre>
  data = c(
    1.0,
    0.2,
    0.2,
    0.2,
    1.0,
    0.2,
    0.2,
    0.2,
    1.0
  ),
  nrow = p
)
sigma0_l \leftarrow t(chol(sigma0))
mu \leftarrow rep(x = 0, times = p)
phi <- matrix(</pre>
  data = c(
    -0.357,
    0.771,
    -0.450,
    0.0,
    -0.511,
    0.729,
    0,
    0,
    -0.693
  ),
  nrow = p
sigma <- matrix(</pre>
  data = c(
    0.24455556,
    0.02201587,
    -0.05004762,
    0.02201587,
```

28 confint.ctmedboot

```
0.07067800,
   0.01539456,
   -0.05004762,
   0.01539456,
   0.07553061
 ),
  nrow = p
)
sigma_l <- t(chol(sigma))</pre>
## measurement model
k <- 3
nu \leftarrow rep(x = 0, times = k)
lambda <- diag(k)</pre>
theta <- 0.2 * diag(k)
theta_l <- t(chol(theta))</pre>
boot <- PBSSMOUFixed(</pre>
  R = 1000L
  path = getwd(),
  prefix = "ou",
  n = n,
  time = time,
  delta_t = delta_t,
  mu0 = mu0,
  sigma0_1 = sigma0_1,
  mu = mu,
  phi = phi,
  sigma_l = sigma_l,
  nu = nu,
  lambda = lambda,
  theta_l = theta_l,
  ncores = parallel::detectCores() - 1,
  seed = 42
)
phi_hat <- phi</pre>
colnames(phi_hat) \leftarrow rownames(phi_hat) \leftarrow c("x", "m", "y")
phi <- extract(object = boot, what = "phi")</pre>
# Specific time interval ------
boot <- BootMed(</pre>
  phi = phi,
  phi_hat = phi_hat,
 delta_t = 1,
 from = "x",
  to = "y",
  med = "m"
)
confint(boot)
confint(boot, type = "bc") # bias-corrected
# Range of time intervals ------
boot <- BootMed(</pre>
  phi = phi,
```

confint.ctmeddelta 29

```
phi_hat = phi_hat,
  delta_t = 1:5,
  from = "x",
  to = "y",
  med = "m"
)
confint(boot)
confint(boot, type = "bc") # bias-corrected
## End(Not run)
```

confint.ctmeddelta

Delta Method Confidence Intervals

## **Description**

Delta Method Confidence Intervals

## Usage

```
## S3 method for class 'ctmeddelta'
confint(object, parm = NULL, level = 0.95, ...)
```

#### **Arguments**

object Object of class ctmeddelta.

parm a specification of which parameters are to be given confidence intervals, either

a vector of numbers or a vector of names. If missing, all parameters are consid-

ered.

level the confidence level required.

... additional arguments.

## Value

Returns a data frame of confidence intervals.

## Author(s)

Ivan Jacob Agaloos Pesigan

30 confint.ctmeddelta

```
phi <- matrix(</pre>
  data = c(
   -0.357, 0.771, -0.450,
   0.0, -0.511, 0.729,
   0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
vcov_phi_vec <- matrix(</pre>
  data = c(
    0.00843, 0.00040, -0.00151,
    -0.00600, -0.00033, 0.00110,
    0.00324, 0.00020, -0.00061,
    0.00040, 0.00374, 0.00016,
    -0.00022, -0.00273, -0.00016,
    0.00009, 0.00150, 0.00012,
    -0.00151, 0.00016, 0.00389,
    0.00103, -0.00007, -0.00283,
    -0.00050, 0.00000, 0.00156,
    -0.00600, -0.00022, 0.00103,
    0.00644, 0.00031, -0.00119,
    -0.00374, -0.00021, 0.00070,
    -0.00033, -0.00273, -0.00007,
    0.00031, 0.00287, 0.00013,
    -0.00014, -0.00170, -0.00012,
    0.00110, -0.00016, -0.00283,
    -0.00119, 0.00013, 0.00297,
    0.00063, -0.00004, -0.00177,
    0.00324, 0.00009, -0.00050,
    -0.00374, -0.00014, 0.00063,
    0.00495, 0.00024, -0.00093,
    0.00020, 0.00150, 0.00000,
    -0.00021, -0.00170, -0.00004,
    0.00024, 0.00214, 0.00012,
    -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
    -0.00093, 0.00012, 0.00223
  ),
  nrow = 9
)
# Specific time interval ------
delta <- DeltaMed(</pre>
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1,
  from = "x",
  to = "y",
  med = "m"
)
```

confint.ctmedmc 31

```
confint(delta, level = 0.95)

# Range of time intervals ------
delta <- DeltaMed(
   phi = phi,
   vcov_phi_vec = vcov_phi_vec,
   delta_t = 1:5,
   from = "x",
   to = "y",
   med = "m"
)
confint(delta, level = 0.95)</pre>
```

confint.ctmedmc

Monte Carlo Method Confidence Intervals

## **Description**

Monte Carlo Method Confidence Intervals

## Usage

```
## S3 method for class 'ctmedmc'
confint(object, parm = NULL, level = 0.95, ...)
```

# Arguments

object Object of class ctmedmc.

parm a specification of which parameters are to be given confidence intervals, either a vector of numbers or a vector of names. If missing, all parameters are considered.

level the confidence level required.
... additional arguments.

## Value

Returns a data frame of confidence intervals.

#### Author(s)

Ivan Jacob Agaloos Pesigan

32 confint.ctmedmc

```
set.seed(42)
phi <- matrix(</pre>
  data = c(
   -0.357, 0.771, -0.450,
   0.0, -0.511, 0.729,
   0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
vcov_phi_vec <- matrix(</pre>
  data = c(
    0.00843, 0.00040, -0.00151,
    -0.00600, -0.00033, 0.00110,
    0.00324, 0.00020, -0.00061,
    0.00040, 0.00374, 0.00016,
    -0.00022, -0.00273, -0.00016,
    0.00009, 0.00150, 0.00012,
    -0.00151, 0.00016, 0.00389,
    0.00103, -0.00007, -0.00283,
    -0.00050, 0.00000, 0.00156,
    -0.00600, -0.00022, 0.00103,
   0.00644, 0.00031, -0.00119,
   -0.00374, -0.00021, 0.00070,
    -0.00033, -0.00273, -0.00007,
    0.00031, 0.00287, 0.00013,
    -0.00014, -0.00170, -0.00012,
   0.00110, -0.00016, -0.00283,
    -0.00119, 0.00013, 0.00297,
    0.00063, -0.00004, -0.00177,
    0.00324, 0.00009, -0.00050,
    -0.00374, -0.00014, 0.00063,
    0.00495, 0.00024, -0.00093,
    0.00020, 0.00150, 0.00000,
    -0.00021, -0.00170, -0.00004,
   0.00024, 0.00214, 0.00012,
   -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
    -0.00093, 0.00012, 0.00223
  ),
 nrow = 9
)
# Specific time interval ------
mc <- MCMed(</pre>
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1,
  from = "x",
  to = "y",
  med = "m",
```

DeltaBeta 33

```
R = 100L # use a large value for R in actual research
)
confint(mc, level = 0.95)

# Range of time intervals ------
mc <- MCMed(
    phi = phi,
    vcov_phi_vec = vcov_phi_vec,
    delta_t = 1:5,
    from = "x",
    to = "y",
    med = "m",
    R = 100L # use a large value for R in actual research
)
confint(mc, level = 0.95)</pre>
```

DeltaBeta

Delta Method Sampling Variance-Covariance Matrix for the Elements of the Matrix of Lagged Coefficients Over a Specific Time Interval or a Range of Time Intervals

## **Description**

This function computes the delta method sampling variance-covariance matrix for the elements of the matrix of lagged coefficients  $\beta$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model's drift matrix  $\Phi$ .

## Usage

```
DeltaBeta(phi, vcov_phi_vec, delta_t, ncores = NULL, tol = 0.01)
```

## **Arguments**

phi	Numeric matrix. The drift matrix $(\Phi)$ , phi should have row and column names pertaining to the variables in the system.
vcov_phi_vec	Numeric matrix. The sampling variance-covariance matrix of $\operatorname{vec}\left(\Phi\right)$ .
delta_t	Vector of positive numbers. Time interval ( $\Delta t$ ).
ncores	Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when the length of delta_t is long.
tol	Numeric. Smallest possible time interval to allow.

#### **Details**

```
See Total().
```

34 DeltaBeta

#### **Delta Method:**

Let  $\theta$  be  $\text{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be  $\text{vec}(\hat{\Phi})$ . By the multivariate central limit theory, the function  $\mathbf{g}$  using  $\hat{\theta}$  as input can be expressed as:

$$\sqrt{n}\left(\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right) - \mathbf{g}\left(\boldsymbol{\theta}\right)\right) \xrightarrow{\mathrm{D}} \mathcal{N}\left(0, \mathbf{J}\boldsymbol{\Gamma}\mathbf{J}'\right)$$

where **J** is the matrix of first-order derivatives of the function **g** with respect to the elements of  $\theta$  and  $\Gamma$  is the asymptotic variance-covariance matrix of  $\hat{\theta}$ .

From the former, we can derive the distribution of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  as follows:

$$\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right) \approx \mathcal{N}\left(\mathbf{g}\left(\boldsymbol{\theta}\right), n^{-1}\mathbf{J}\boldsymbol{\Gamma}\mathbf{J}'\right)$$

The uncertainty associated with the estimator  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  is, therefore, given by  $n^{-1}\mathbf{J}\Gamma\mathbf{J}'$ . When  $\Gamma$  is unknown, by substitution, we can use the estimated sampling variance-covariance matrix of  $\hat{\boldsymbol{\theta}}$ , that is,  $\hat{\mathbb{V}}\left(\hat{\boldsymbol{\theta}}\right)$  for  $n^{-1}\Gamma$ . Therefore, the sampling variance-covariance matrix of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  is given by

$$\mathbf{g}\left(\hat{oldsymbol{ heta}}
ight)pprox\mathcal{N}\left(\mathbf{g}\left(oldsymbol{ heta}
ight),\mathbf{J}\hat{\mathbb{V}}\left(\hat{oldsymbol{ heta}}
ight)\mathbf{J}'
ight).$$

#### Value

Returns an object of class ctmeddelta which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("DeltaBeta").

**output** A list the length of which is equal to the length of delta\_t.

Each element in the output list has the following elements:

delta\_t Time interval.

jacobian Jacobian matrix.

est Estimated elements of the matrix of lagged coefficients.

**vcov** Sampling variance-covariance matrix of estimated elements of the matrix of lagged coefficients.

#### Author(s)

Ivan Jacob Agaloos Pesigan

DeltaBeta 35

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
phi <- matrix(</pre>
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
vcov_phi_vec <- matrix(</pre>
  data = c(
    0.00843, 0.00040, -0.00151,
    -0.00600, -0.00033, 0.00110,
    0.00324, 0.00020, -0.00061,
    0.00040, 0.00374, 0.00016,
    -0.00022, -0.00273, -0.00016,
    0.00009, 0.00150, 0.00012,
    -0.00151, 0.00016, 0.00389,
    0.00103, -0.00007, -0.00283,
    -0.00050, 0.00000, 0.00156,
    -0.00600, -0.00022, 0.00103,
    0.00644, 0.00031, -0.00119,
    -0.00374, -0.00021, 0.00070,
    -0.00033, -0.00273, -0.00007,
    0.00031, 0.00287, 0.00013,
    -0.00014, -0.00170, -0.00012,
    0.00110, -0.00016, -0.00283,
    -0.00119, 0.00013, 0.00297,
    0.00063, -0.00004, -0.00177,
```

36 DeltaBetaStd

```
0.00324, 0.00009, -0.00050,
   -0.00374, -0.00014, 0.00063,
   0.00495, 0.00024, -0.00093,
   0.00020, 0.00150, 0.00000,
   -0.00021, -0.00170, -0.00004,
   0.00024, 0.00214, 0.00012,
   -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
   -0.00093, 0.00012, 0.00223
 ),
 nrow = 9
)
# Specific time interval ------
DeltaBeta(
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1
)
# Range of time intervals ------
delta <- DeltaBeta(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1:5
plot(delta)
# Methods ------
# DeltaBeta has a number of methods including
# print, summary, confint, and plot
print(delta)
summary(delta)
confint(delta, level = 0.95)
plot(delta)
```

DeltaBetaStd

Delta Method Sampling Variance-Covariance Matrix for the Elements of the Standardized Matrix of Lagged Coefficients Over a Specific Time Interval or a Range of Time Intervals

# Description

This function computes the delta method sampling variance-covariance matrix for the elements of the standardized matrix of lagged coefficients  $\beta$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model's drift matrix  $\Phi$  and process noise covariance matrix  $\Sigma$ .

DeltaBetaStd 37

#### Usage

DeltaBetaStd(phi, sigma, vcov\_theta, delta\_t, ncores = NULL, tol = 0.01)

### **Arguments**

Numeric matrix. The drift matrix  $(\Phi)$ , phi should have row and column names pertaining to the variables in the system.

Sigma Numeric matrix. The process noise covariance matrix  $(\Sigma)$ .

VCOV\_theta Numeric matrix. The sampling variance-covariance matrix of  $\operatorname{vec}(\Phi)$  and  $\operatorname{vech}(\Sigma)$  delta\_t Numeric. Time interval  $(\Delta t)$ .

Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.

tol Numeric. Smallest possible time interval to allow.

#### **Details**

See TotalStd().

#### **Delta Method:**

Let  $\theta$  be a vector that combines  $\text{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise and  $\text{vech}(\Sigma)$ , that is, the unique elements of the  $\Sigma$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be a vector that combines  $\text{vec}(\hat{\Phi})$  and  $\text{vech}(\hat{\Sigma})$ . By the multivariate central limit theory, the function  $\mathbf{g}$  using  $\hat{\theta}$  as input can be expressed as:

$$\sqrt{n}\left(\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right) - \mathbf{g}\left(\boldsymbol{\theta}\right)\right) \xrightarrow{\mathrm{D}} \mathcal{N}\left(0, \mathbf{J}\boldsymbol{\Gamma}\mathbf{J}'\right)$$

where **J** is the matrix of first-order derivatives of the function **g** with respect to the elements of  $\theta$  and  $\Gamma$  is the asymptotic variance-covariance matrix of  $\hat{\theta}$ .

From the former, we can derive the distribution of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  as follows:

$$\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right) \approx \mathcal{N}\left(\mathbf{g}\left(\boldsymbol{\theta}\right), n^{-1} \mathbf{J} \boldsymbol{\Gamma} \mathbf{J}'\right)$$

The uncertainty associated with the estimator  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  is, therefore, given by  $n^{-1}\mathbf{J}\Gamma\mathbf{J}'$ . When  $\Gamma$  is unknown, by substitution, we can use the estimated sampling variance-covariance matrix of  $\hat{\boldsymbol{\theta}}$ , that is,  $\hat{\mathbb{V}}\left(\hat{\boldsymbol{\theta}}\right)$  for  $n^{-1}\Gamma$ . Therefore, the sampling variance-covariance matrix of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  is given by

$$\mathbf{g}\left(\hat{\boldsymbol{ heta}}\right) pprox \mathcal{N}\left(\mathbf{g}\left(\boldsymbol{ heta}
ight), \mathbf{J}\hat{\mathbb{V}}\left(\hat{\boldsymbol{ heta}}
ight) \mathbf{J}'
ight).$$

### Value

Returns an object of class ctmeddelta which is a list with the following elements:

call Function call.

args Function arguments.

38 DeltaBetaStd

fun Function used ("DeltaBetaStd").

**output** A list the length of which is equal to the length of delta\_t.

Each element in the output list has the following elements:

delta t Time interval.

jacobian Jacobian matrix.

est Estimated elements of the standardized matrix of lagged coefficients.

**vcov** Sampling variance-covariance matrix of estimated elements of the standardized matrix of lagged coefficients.

### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
sigma <- matrix(
  data = c(
    0.24455556, 0.02201587, -0.05004762,</pre>
```

DeltaBetaStd 39

```
0.02201587, 0.07067800, 0.01539456,
    -0.05004762, 0.01539456, 0.07553061
 ),
 nrow = 3
)
vcov_theta <- matrix(
 data = c(
    0.00843, 0.00040, -0.00151, -0.00600, -0.00033,
   0.00110, 0.00324, 0.00020, -0.00061, -0.00115,
   0.00011, 0.00015, 0.00001, -0.00002, -0.00001,
   0.00040, 0.00374, 0.00016, -0.00022, -0.00273,
    -0.00016, 0.00009, 0.00150, 0.00012, -0.00010,
    -0.00026, 0.00002, 0.00012, 0.00004, -0.00001,
    -0.00151, 0.00016, 0.00389, 0.00103, -0.00007,
    -0.00283, -0.00050, 0.00000, 0.00156, 0.00021,
    -0.00005, -0.00031, 0.00001, 0.00007, 0.00006,
   -0.00600, -0.00022, 0.00103, 0.00644, 0.00031,
   -0.00119, -0.00374, -0.00021, 0.00070, 0.00064,
    -0.00015, -0.00005, 0.00000, 0.00003, -0.00001,
    -0.00033, -0.00273, -0.00007, 0.00031, 0.00287,
    0.00013, -0.00014, -0.00170, -0.00012, 0.00006,
    0.00014, -0.00001, -0.00015, 0.00000, 0.00001,
    0.00110, -0.00016, -0.00283, -0.00119, 0.00013,
    0.00297, 0.00063, -0.00004, -0.00177, -0.00013,
    0.00005, 0.00017, -0.00002, -0.00008, 0.00001,
   0.00324, 0.00009, -0.00050, -0.00374, -0.00014,
    0.00063, 0.00495, 0.00024, -0.00093, -0.00020,
    0.00006, -0.00010, 0.00000, -0.00001, 0.00004,
   0.00020, 0.00150, 0.00000, -0.00021, -0.00170,
    -0.00004, 0.00024, 0.00214, 0.00012, -0.00002,
   -0.00004, 0.00000, 0.00006, -0.00005, -0.00001,
   -0.00061, 0.00012, 0.00156, 0.00070, -0.00012,
   -0.00177, -0.00093, 0.00012, 0.00223, 0.00004,
    -0.00002, -0.00003, 0.00001, 0.00003, -0.00013,
    -0.00115, -0.00010, 0.00021, 0.00064, 0.00006,
    -0.00013, -0.00020, -0.00002, 0.00004, 0.00057,
    0.00001, -0.00009, 0.00000, 0.00000, 0.00001,
    0.00011, -0.00026, -0.00005, -0.00015, 0.00014,
   0.00005, 0.00006, -0.00004, -0.00002, 0.00001,
    0.00012, 0.00001, 0.00000, -0.00002, 0.00000,
    0.00015, 0.00002, -0.00031, -0.00005, -0.00001,
   0.00017, -0.00010, 0.00000, -0.00003, -0.00009,
    0.00001, 0.00014, 0.00000, 0.00000, -0.00005,
   0.00001, 0.00012, 0.00001, 0.00000, -0.00015,
    -0.00002, 0.00000, 0.00006, 0.00001, 0.00000,
    0.00000, 0.00000, 0.00010, 0.00001, 0.00000,
    -0.00002, 0.00004, 0.00007, 0.00003, 0.00000,
    -0.00008, -0.00001, -0.00005, 0.00003, 0.00000,
   -0.00002, 0.00000, 0.00001, 0.00005, 0.00001,
    -0.00001, -0.00001, 0.00006, -0.00001, 0.00001,
   0.00001, 0.00004, -0.00001, -0.00013, 0.00001,
   0.00000, -0.00005, 0.00000, 0.00001, 0.00012
 ),
```

40 DeltaIndirectCentral

```
nrow = 15
)
# Specific time interval ------
DeltaBetaStd(
 phi = phi,
 sigma = sigma,
 vcov_theta = vcov_theta,
 delta_t = 1
)
# Range of time intervals ------
delta <- DeltaBetaStd(</pre>
 phi = phi,
 sigma = sigma,
 vcov_theta = vcov_theta,
 delta_t = 1:5
)
plot(delta)
# Methods ------
# DeltaBetaStd has a number of methods including
# print, summary, confint, and plot
print(delta)
summary(delta)
confint(delta, level = 0.95)
plot(delta)
```

DeltaIndirectCentral

Delta Method Sampling Variance-Covariance Matrix for the Indirect Effect Centrality Over a Specific Time Interval or a Range of Time Intervals

### **Description**

This function computes the delta method sampling variance-covariance matrix for the indirect effect centrality over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model's drift matrix  $\Phi$ .

## Usage

```
DeltaIndirectCentral(phi, vcov_phi_vec, delta_t, ncores = NULL, tol = 0.01)
```

## Arguments

phi Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names

pertaining to the variables in the system.

vcov\_phi\_vec Numeric matrix. The sampling variance-covariance matrix of  $vec(\Phi)$ .

DeltaIndirectCentral 41

delta\_t Vector of positive numbers. Time interval ( $\Delta t$ ).

ncores Positive integer. Number of cores to use. If ncores = NULL, use a single core.

Consider using multiple cores when the length of delta\_t is long.

tol Numeric. Smallest possible time interval to allow.

#### **Details**

See IndirectCentral() more details.

#### **Delta Method:**

Let  $\theta$  be  $\operatorname{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be  $\operatorname{vec}(\hat{\Phi})$ . By the multivariate central limit theory, the function  $\mathbf{g}$  using  $\hat{\theta}$  as input can be expressed as:

$$\sqrt{n}\left(\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right) - \mathbf{g}\left(\boldsymbol{\theta}\right)\right) \xrightarrow{\mathrm{D}} \mathcal{N}\left(0, \mathbf{J}\boldsymbol{\Gamma}\mathbf{J}'\right)$$

where **J** is the matrix of first-order derivatives of the function **g** with respect to the elements of  $\theta$  and  $\Gamma$  is the asymptotic variance-covariance matrix of  $\hat{\theta}$ .

From the former, we can derive the distribution of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  as follows:

$$\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right) \approx \mathcal{N}\left(\mathbf{g}\left(\boldsymbol{\theta}\right), n^{-1}\mathbf{J}\boldsymbol{\Gamma}\mathbf{J}'\right)$$

The uncertainty associated with the estimator  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  is, therefore, given by  $n^{-1}\mathbf{J}\Gamma\mathbf{J}'$ . When  $\Gamma$  is unknown, by substitution, we can use the estimated sampling variance-covariance matrix of  $\hat{\boldsymbol{\theta}}$ , that is,  $\hat{\mathbb{V}}\left(\hat{\boldsymbol{\theta}}\right)$  for  $n^{-1}\Gamma$ . Therefore, the sampling variance-covariance matrix of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  is given by

$$\mathbf{g}\left(\hat{oldsymbol{ heta}}
ight)pprox\mathcal{N}\left(\mathbf{g}\left(oldsymbol{ heta}
ight),\mathbf{J}\hat{\mathbb{V}}\left(\hat{oldsymbol{ heta}}
ight)\mathbf{J}'
ight).$$

## Value

Returns an object of class ctmeddelta which is a list with the following elements:

call Function call.

args Function arguments.

**fun** Function used ("DeltaIndirectCentral").

**output** A list the length of which is equal to the length of delta\_t.

Each element in the output list has the following elements:

delta\_t Time interval.

jacobian Jacobian matrix.

est Estimated indirect effect centrality.

vcov Sampling variance-covariance matrix of estimated indirect effect centrality.

42 DeltaIndirectCentral

### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
phi <- matrix(</pre>
 data = c(
   -0.357, 0.771, -0.450,
   0.0, -0.511, 0.729,
   0, 0, -0.693
 ),
 nrow = 3
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
vcov_phi_vec <- matrix(</pre>
 data = c(
    0.002704274, -0.001475275, 0.000949122,
    -0.001619422, 0.000885122, -0.000569404,
    0.00085493, -0.000465824, 0.000297815,
    -0.001475275, 0.004428442, -0.002642303,
    0.000980573, -0.00271817, 0.001618805,
    -0.000586921, 0.001478421, -0.000871547,
    0.000949122, -0.002642303, 0.006402668,
    -0.000697798, 0.001813471, -0.004043138,
    0.000463086, -0.001120949, 0.002271711,
    -0.001619422, 0.000980573, -0.000697798,
    0.002079286, -0.001152501, 0.000753,
    -0.001528701, 0.000820587, -0.000517524,
    0.000885122, -0.00271817, 0.001813471,
    -0.001152501, 0.00342605, -0.002075005,
```

```
0.000899165, -0.002532849, 0.001475579,
   -0.000569404, 0.001618805, -0.004043138,
   0.000753, -0.002075005, 0.004984032,
   -0.000622255, 0.001634917, -0.003705661,
   0.00085493, -0.000586921, 0.000463086,
   -0.001528701, 0.000899165, -0.000622255,
   0.002060076, -0.001096684, 0.000686386,
   -0.000465824, 0.001478421, -0.001120949,
   0.000820587, -0.002532849, 0.001634917,
   -0.001096684, 0.003328692, -0.001926088,
   0.000297815, -0.000871547, 0.002271711,
   -0.000517524, 0.001475579, -0.003705661,
   0.000686386, -0.001926088, 0.004726235
 ),
 nrow = 9
)
# Specific time interval ------
DeltaIndirectCentral(
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1
)
# Range of time intervals ------
delta <- DeltaIndirectCentral(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1:5
)
plot(delta)
# Methods ------
# DeltaIndirectCentral has a number of methods including
# print, summary, confint, and plot
print(delta)
summary(delta)
confint(delta, level = 0.95)
plot(delta)
```

DeltaMed

Delta Method Sampling Variance-Covariance Matrix for the Total, Direct, and Indirect Effects of X on Y Through M Over a Specific Time Interval or a Range of Time Intervals

### **Description**

This function computes the delta method sampling variance-covariance matrix for the total, direct, and indirect effects of the independent variable X on the dependent variable Y through media-

tor variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model's drift matrix  $\mathbf{\Phi}$ .

### Usage

DeltaMed(phi, vcov\_phi\_vec, delta\_t, from, to, med, ncores = NULL, tol = 0.01)

# **Arguments**

phi Numeric matrix. The drift matrix  $(\Phi)$ , phi should have row and column names

pertaining to the variables in the system.

vcov\_phi\_vec Numeric matrix. The sampling variance-covariance matrix of  $\text{vec}(\Phi)$ .

delta\_t Vector of positive numbers. Time interval ( $\Delta t$ ).

from Character string. Name of the independent variable X in phi.

to Character string. Name of the dependent variable Y in phi.

med Character vector. Name/s of the mediator variable/s in phi.

ncores Positive integer. Number of cores to use. If ncores = NULL, use a single core.

Consider using multiple cores when the length of delta\_t is long.

tol Numeric. Smallest possible time interval to allow.

#### **Details**

See Total(), Direct(), and Indirect() for more details.

### **Delta Method:**

Let  $\theta$  be  $\text{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be  $\text{vec}(\hat{\Phi})$ . By the multivariate central limit theory, the function  $\mathbf{g}$  using  $\hat{\theta}$  as input can be expressed as:

$$\sqrt{n}\left(\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)-\mathbf{g}\left(\boldsymbol{\theta}\right)\right) \xrightarrow{\mathbf{D}} \mathcal{N}\left(0,\mathbf{J}\boldsymbol{\Gamma}\mathbf{J}'\right)$$

where **J** is the matrix of first-order derivatives of the function **g** with respect to the elements of  $\theta$  and  $\Gamma$  is the asymptotic variance-covariance matrix of  $\hat{\theta}$ .

From the former, we can derive the distribution of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  as follows:

$$\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right) \approx \mathcal{N}\left(\mathbf{g}\left(\boldsymbol{\theta}\right), n^{-1}\mathbf{J}\mathbf{\Gamma}\mathbf{J}'\right)$$

The uncertainty associated with the estimator  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  is, therefore, given by  $n^{-1}\mathbf{J}\Gamma\mathbf{J}'$ . When  $\Gamma$  is unknown, by substitution, we can use the estimated sampling variance-covariance matrix of  $\hat{\boldsymbol{\theta}}$ , that is,  $\hat{\mathbb{V}}\left(\hat{\boldsymbol{\theta}}\right)$  for  $n^{-1}\Gamma$ . Therefore, the sampling variance-covariance matrix of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  is given by

$$\mathbf{g}\left(\hat{oldsymbol{ heta}}
ight)pprox\mathcal{N}\left(\mathbf{g}\left(oldsymbol{ heta}
ight),\mathbf{J}\hat{\mathbb{V}}\left(\hat{oldsymbol{ heta}}
ight)\mathbf{J}'
ight).$$

#### Value

Returns an object of class ctmeddelta which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("DeltaMed").

**output** A list the length of which is equal to the length of delta\_t.

Each element in the output list has the following elements:

delta\_t Time interval.

jacobian Jacobian matrix.

est Estimated total, direct, and indirect effects.

vcov Sampling variance-covariance matrix of the estimated total, direct, and indirect effects.

#### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
),
  nrow = 3</pre>
```

```
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
vcov_phi_vec <- matrix(</pre>
 data = c(
   0.00843, 0.00040, -0.00151,
   -0.00600, -0.00033, 0.00110,
   0.00324, 0.00020, -0.00061,
   0.00040, 0.00374, 0.00016,
   -0.00022, -0.00273, -0.00016,
   0.00009, 0.00150, 0.00012,
   -0.00151, 0.00016, 0.00389,
   0.00103, -0.00007, -0.00283,
   -0.00050, 0.00000, 0.00156,
   -0.00600, -0.00022, 0.00103,
   0.00644, 0.00031, -0.00119,
   -0.00374, -0.00021, 0.00070,
   -0.00033, -0.00273, -0.00007,
   0.00031, 0.00287, 0.00013,
   -0.00014, -0.00170, -0.00012,
   0.00110, -0.00016, -0.00283,
   -0.00119, 0.00013, 0.00297,
   0.00063, -0.00004, -0.00177,
   0.00324, 0.00009, -0.00050,
   -0.00374, -0.00014, 0.00063,
   0.00495, 0.00024, -0.00093,
   0.00020, 0.00150, 0.00000,
   -0.00021, -0.00170, -0.00004,
   0.00024, 0.00214, 0.00012,
   -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
   -0.00093, 0.00012, 0.00223
 ),
 nrow = 9
)
# Specific time interval ------
DeltaMed(
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1,
 from = "x",
 to = "y",
 med = "m"
)
# Range of time intervals ------
delta <- DeltaMed(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1:5,
 from = "x",
 to = "y",
 med = "m"
```

DeltaMedStd 47

```
plot(delta)

# Methods ------

# DeltaMed has a number of methods including

# print, summary, confint, and plot
print(delta)
summary(delta)
confint(delta, level = 0.95)
plot(delta)
```

DeltaMedStd

Delta Method Sampling Variance-Covariance Matrix for the Standardized Total, Direct, and Indirect Effects of X on Y Through M Over a Specific Time Interval or a Range of Time Intervals

# **Description**

This function computes the delta method sampling variance-covariance matrix for the standardized total, direct, and indirect effects of the independent variable X on the dependent variable Y through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model's drift matrix  $\mathbf{\Phi}$  and process noise covariance matrix  $\mathbf{\Sigma}$ .

# Usage

```
DeltaMedStd(
   phi,
   sigma,
   vcov_theta,
   delta_t,
   from,
   to,
   med,
   ncores = NULL,
   tol = 0.01
)
```

# **Arguments**

phi	Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system.
	pertaining to the variables in the system.
sigma	Numeric matrix. The process noise covariance matrix $(\Sigma)$ .
vcov_theta	Numeric matrix. The sampling variance-covariance matrix of $\operatorname{vec}\left(\mathbf{\Phi}\right)$ and $\operatorname{vech}\left(\mathbf{\Sigma}\right)$
delta_t	Numeric. Time interval $(\Delta t)$ .
from	Character string. Name of the independent variable $X$ in phi.

character string. Name of the dependent variable Y in phi.

Character vector. Name/s of the mediator variable/s in phi.

Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.

Numeric. Smallest possible time interval to allow.

### **Details**

48

See TotalStd(), DirectStd(), and IndirectStd() for more details.

#### **Delta Method:**

Let  $\theta$  be a vector that combines  $\text{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise and  $\text{vech}(\Sigma)$ , that is, the unique elements of the  $\Sigma$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be a vector that combines  $\text{vec}(\hat{\Phi})$  and  $\text{vech}(\hat{\Sigma})$ . By the multivariate central limit theory, the function  $\mathbf{g}$  using  $\hat{\theta}$  as input can be expressed as:

$$\sqrt{n}\left(\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right) - \mathbf{g}\left(\boldsymbol{\theta}\right)\right) \xrightarrow{\mathrm{D}} \mathcal{N}\left(0, \mathbf{J}\mathbf{\Gamma}\mathbf{J}'\right)$$

where **J** is the matrix of first-order derivatives of the function **g** with respect to the elements of  $\theta$  and  $\Gamma$  is the asymptotic variance-covariance matrix of  $\hat{\theta}$ .

From the former, we can derive the distribution of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  as follows:

$$\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right) \approx \mathcal{N}\left(\mathbf{g}\left(\boldsymbol{\theta}\right), n^{-1}\mathbf{J}\boldsymbol{\Gamma}\mathbf{J}'\right)$$

The uncertainty associated with the estimator  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  is, therefore, given by  $n^{-1}\mathbf{J}\Gamma\mathbf{J}'$ . When  $\Gamma$  is unknown, by substitution, we can use the estimated sampling variance-covariance matrix of  $\hat{\boldsymbol{\theta}}$ , that is,  $\hat{\mathbb{V}}\left(\hat{\boldsymbol{\theta}}\right)$  for  $n^{-1}\Gamma$ . Therefore, the sampling variance-covariance matrix of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  is given by

$$\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right) \approx \mathcal{N}\left(\mathbf{g}\left(\boldsymbol{\theta}\right), \mathbf{J}\hat{\mathbb{V}}\left(\hat{\boldsymbol{\theta}}\right) \mathbf{J}'\right).$$

## Value

Returns an object of class ctmeddelta which is a list with the following elements:

call Function call.

args Function arguments.

**fun** Function used ("DeltaMedStd").

**output** A list the length of which is equal to the length of delta\_t.

Each element in the output list has the following elements:

**delta\_t** Time interval.

jacobian Jacobian matrix.

est Estimated standardized total, direct, and indirect effects.

**vcov** Sampling variance-covariance matrix of the estimated standardized total, direct, and indirect effects.

DeltaMedStd 49

### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

```
phi <- matrix(</pre>
 data = c(
   -0.357, 0.771, -0.450,
   0.0, -0.511, 0.729,
   0, 0, -0.693
 ),
 nrow = 3
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
sigma <- matrix(</pre>
 data = c(
   0.24455556, 0.02201587, -0.05004762,
   0.02201587, 0.07067800, 0.01539456,
    -0.05004762, 0.01539456, 0.07553061
 ),
 nrow = 3
)
vcov_theta <- matrix(</pre>
 data = c(
    0.00843, 0.00040, -0.00151, -0.00600, -0.00033,
    0.00110, 0.00324, 0.00020, -0.00061, -0.00115,
    0.00011, 0.00015, 0.00001, -0.00002, -0.00001,
    0.00040, 0.00374, 0.00016, -0.00022, -0.00273,
    -0.00016, 0.00009, 0.00150, 0.00012, -0.00010,
    -0.00026, 0.00002, 0.00012, 0.00004, -0.00001,
```

50 DeltaMedStd

```
-0.00151, 0.00016, 0.00389, 0.00103, -0.00007,
   -0.00283, -0.00050, 0.00000, 0.00156, 0.00021,
   -0.00005, -0.00031, 0.00001, 0.00007, 0.00006,
   -0.00600, -0.00022, 0.00103, 0.00644, 0.00031,
   -0.00119, -0.00374, -0.00021, 0.00070, 0.00064,
   -0.00015, -0.00005, 0.00000, 0.00003, -0.00001,
    -0.00033, -0.00273, -0.00007, 0.00031, 0.00287,
    0.00013, -0.00014, -0.00170, -0.00012, 0.00006,
    0.00014, -0.00001, -0.00015, 0.00000, 0.00001,
    0.00110, -0.00016, -0.00283, -0.00119, 0.00013,
    0.00297, 0.00063, -0.00004, -0.00177, -0.00013,
   0.00005, 0.00017, -0.00002, -0.00008, 0.00001,
    0.00324, 0.00009, -0.00050, -0.00374, -0.00014,
    0.00063, 0.00495, 0.00024, -0.00093, -0.00020,
    0.00006, -0.00010, 0.00000, -0.00001, 0.00004,
   0.00020, 0.00150, 0.00000, -0.00021, -0.00170,
    -0.00004, 0.00024, 0.00214, 0.00012, -0.00002,
    -0.00004, 0.00000, 0.00006, -0.00005, -0.00001,
    -0.00061, 0.00012, 0.00156, 0.00070, -0.00012,
    -0.00177, -0.00093, 0.00012, 0.00223, 0.00004,
    -0.00002, -0.00003, 0.00001, 0.00003, -0.00013,
    -0.00115, -0.00010, 0.00021, 0.00064, 0.00006,
    -0.00013, -0.00020, -0.00002, 0.00004, 0.00057,
    0.00001, -0.00009, 0.00000, 0.00000, 0.00001,
    0.00011, -0.00026, -0.00005, -0.00015, 0.00014,
    0.00005, 0.00006, -0.00004, -0.00002, 0.00001,
    0.00012, 0.00001, 0.00000, -0.00002, 0.00000,
    0.00015, 0.00002, -0.00031, -0.00005, -0.00001,
   0.00017, -0.00010, 0.00000, -0.00003, -0.00009,
   0.00001, 0.00014, 0.00000, 0.00000, -0.00005,
   0.00001, 0.00012, 0.00001, 0.00000, -0.00015,
    -0.00002, 0.00000, 0.00006, 0.00001, 0.00000,
   0.00000, 0.00000, 0.00010, 0.00001, 0.00000,
    -0.00002, 0.00004, 0.00007, 0.00003, 0.00000,
    -0.00008, -0.00001, -0.00005, 0.00003, 0.00000,
   -0.00002, 0.00000, 0.00001, 0.00005, 0.00001,
    -0.00001, -0.00001, 0.00006, -0.00001, 0.00001,
   0.00001, 0.00004, -0.00001, -0.00013, 0.00001,
    0.00000, -0.00005, 0.00000, 0.00001, 0.00012
 ),
 nrow = 15
)
# Specific time interval -------
DeltaMedStd(
 phi = phi,
 sigma = sigma,
 vcov_theta = vcov_theta,
 delta_t = 1,
 from = "x",
 to = "y",
 med = "m"
```

DeltaTotalCentral 51

```
# Range of time intervals ------
delta <- DeltaMedStd(</pre>
 phi = phi,
 sigma = sigma,
 vcov_theta = vcov_theta,
 delta_t = 1:5,
 from = "x",
 to = "y",
 med = "m"
plot(delta)
# Methods ------
# DeltaMedStd has a number of methods including
# print, summary, confint, and plot
print(delta)
summary(delta)
confint(delta, level = 0.95)
plot(delta)
```

DeltaTotalCentral

Delta Method Sampling Variance-Covariance Matrix for the Total Effect Centrality Over a Specific Time Interval or a Range of Time Intervals

# **Description**

This function computes the delta method sampling variance-covariance matrix for the total effect centrality over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model's drift matrix  $\Phi$ .

# Usage

```
DeltaTotalCentral(phi, vcov_phi_vec, delta_t, ncores = NULL, tol = 0.01)
```

# **Arguments**

phi	Numeric matrix. The drift matrix $(\Phi)$ . phi should have row and column names pertaining to the variables in the system.
vcov_phi_vec	Numeric matrix. The sampling variance-covariance matrix of $\operatorname{vec}\left(\mathbf{\Phi}\right)$ .
delta_t	Vector of positive numbers. Time interval $(\Delta t)$ .
ncores	Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when the length of delta_t is long.
tol	Numeric. Smallest possible time interval to allow.

### **Details**

See TotalCentral() more details.

## Delta Method:

Let  $\theta$  be  $\operatorname{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be  $\operatorname{vec}(\hat{\Phi})$ . By the multivariate central limit theory, the function  $\mathbf{g}$  using  $\hat{\theta}$  as input can be expressed as:

$$\sqrt{n}\left(\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right) - \mathbf{g}\left(\boldsymbol{\theta}\right)\right) \xrightarrow{\mathrm{D}} \mathcal{N}\left(0, \mathbf{J}\boldsymbol{\Gamma}\mathbf{J}'\right)$$

where **J** is the matrix of first-order derivatives of the function **g** with respect to the elements of  $\theta$  and  $\Gamma$  is the asymptotic variance-covariance matrix of  $\hat{\theta}$ .

From the former, we can derive the distribution of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  as follows:

$$\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right) \approx \mathcal{N}\left(\mathbf{g}\left(\boldsymbol{\theta}\right), n^{-1}\mathbf{J}\mathbf{\Gamma}\mathbf{J}'\right)$$

The uncertainty associated with the estimator  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  is, therefore, given by  $n^{-1}\mathbf{J}\Gamma\mathbf{J}'$ . When  $\Gamma$  is unknown, by substitution, we can use the estimated sampling variance-covariance matrix of  $\hat{\boldsymbol{\theta}}$ , that is,  $\hat{\mathbb{V}}\left(\hat{\boldsymbol{\theta}}\right)$  for  $n^{-1}\Gamma$ . Therefore, the sampling variance-covariance matrix of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  is given by

$$\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right) \approx \mathcal{N}\left(\mathbf{g}\left(\boldsymbol{\theta}\right), \mathbf{J}\hat{\mathbb{V}}\left(\hat{\boldsymbol{\theta}}\right) \mathbf{J}'\right).$$

## Value

Returns an object of class ctmeddelta which is a list with the following elements:

call Function call.

args Function arguments.

**fun** Function used ("DeltaTotalCentral").

**output** A list the length of which is equal to the length of delta\_t.

Each element in the output list has the following elements:

delta\_t Time interval.

jacobian Jacobian matrix.

est Estimated total effect centrality.

vcov Sampling variance-covariance matrix of estimated total effect centrality.

## Author(s)

Ivan Jacob Agaloos Pesigan

DeltaTotalCentral 53

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
phi <- matrix(</pre>
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) \leftarrow rownames(phi) \leftarrow c("x", "m", "y")
vcov_phi_vec <- matrix(</pre>
  data = c(
    0.00843, 0.00040, -0.00151,
    -0.00600, -0.00033, 0.00110,
    0.00324, 0.00020, -0.00061,
    0.00040, 0.00374, 0.00016,
    -0.00022, -0.00273, -0.00016,
    0.00009, 0.00150, 0.00012,
    -0.00151, 0.00016, 0.00389,
    0.00103, -0.00007, -0.00283,
    -0.00050, 0.00000, 0.00156,
    -0.00600, -0.00022, 0.00103,
    0.00644, 0.00031, -0.00119,
    -0.00374, -0.00021, 0.00070,
    -0.00033, -0.00273, -0.00007,
    0.00031, 0.00287, 0.00013,
    -0.00014, -0.00170, -0.00012,
    0.00110, -0.00016, -0.00283,
    -0.00119, 0.00013, 0.00297,
    0.00063, -0.00004, -0.00177,
    0.00324, 0.00009, -0.00050,
```

54 Direct

```
-0.00374, -0.00014, 0.00063,
   0.00495, 0.00024, -0.00093,
   0.00020, 0.00150, 0.00000,
   -0.00021, -0.00170, -0.00004,
   0.00024, 0.00214, 0.00012,
   -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
   -0.00093, 0.00012, 0.00223
 ),
 nrow = 9
)
# Specific time interval ------
DeltaTotalCentral(
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1
# Range of time intervals ------
delta <- DeltaTotalCentral(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1:5
plot(delta)
# Methods -----
# DeltaTotalCentral has a number of methods including
# print, summary, confint, and plot
print(delta)
summary(delta)
confint(delta, level = 0.95)
plot(delta)
```

Direct

Direct Effect of X on Y Over a Specific Time Interval

# Description

This function computes the direct effect of the independent variable X on the dependent variable Y through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  using the first-order stochastic differential equation model's drift matrix  $\mathbf{\Phi}$ .

## Usage

```
Direct(phi, delta_t, from, to, med)
```

Direct 55

#### **Arguments**

phi	Numeric matrix. The drift matrix $(\Phi)$ . phi should have row and column names pertaining to the variables in the system.
delta_t	Numeric. Time interval ( $\Delta t$ ).
from	Character string. Name of the independent variable $X$ in phi.
to	Character string. Name of the dependent variable $Y$ in phi.
med	Character vector. Name/s of the mediator variable/s in phi.

#### **Details**

The direct effect of the independent variable X on the dependent variable Y relative to some mediator variables  $\mathbf{m}$  is given by

$$Direct_{\Delta t_{i,j}} = \exp(\Delta t \mathbf{D} \mathbf{\Phi} \mathbf{D})_{i,j}$$

where  $\Phi$  denotes the drift matrix,  $\mathbf{D}$  a diagonal matrix where the diagonal elements corresponding to mediator variables  $\mathbf{m}$  are set to zero and the rest to one, i the row index of Y in  $\Phi$ , j the column index of X in  $\Phi$ , and  $\Delta t$  the time interval.

## **Linear Stochastic Differential Equation Model:**

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{\nu} + \boldsymbol{\Lambda} \boldsymbol{\eta}_{i,t} + \boldsymbol{\varepsilon}_{i,t}, \quad ext{with} \quad \boldsymbol{\varepsilon}_{i,t} \sim \mathcal{N}\left(\mathbf{0}, \boldsymbol{\Theta}\right)$$

where  $\mathbf{y}_{i,t}$ ,  $\boldsymbol{\eta}_{i,t}$ , and  $\boldsymbol{\varepsilon}_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\boldsymbol{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\boldsymbol{\eta}_{i,t}$  a vector of latent random variables, and  $\boldsymbol{\varepsilon}_{i,t}$  a vector of random measurement errors, at time t and individual i.  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\boldsymbol{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\boldsymbol{\varepsilon}$ .

An alternative representation of the measurement error is given by

$$oldsymbol{arepsilon}_{i,t} = oldsymbol{\Theta}^{rac{1}{2}} \mathbf{z}_{i,t}, \quad ext{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}\left(\mathbf{0}, \mathbf{I}\right)$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $\left(\Theta^{\frac{1}{2}}\right)\left(\Theta^{\frac{1}{2}}\right)' = \Theta$ . The dynamic structure is given by

$$\mathrm{d}\boldsymbol{\eta}_{i,t} = \left(\boldsymbol{\iota} + \boldsymbol{\Phi} \boldsymbol{\eta}_{i,t}\right) \mathrm{d}t + \boldsymbol{\Sigma}^{\frac{1}{2}} \mathrm{d}\mathbf{W}_{i,t}$$

where  $\iota$  is a term which is unobserved and constant over time,  $\Phi$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\Sigma$  is the matrix of volatility or randomness in the process, and  $\mathrm{d}W$  is a Wiener process or Brownian motion, which represents random fluctuations.

# Value

Returns an object of class ctmedeffect which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("Direct").

output The direct effect.

56 Direct

### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
phi <- matrix(</pre>
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
delta_t <- 1
Direct(
  phi = phi,
  delta_t = delta_t,
  from = "x",
  to = "y",
  med = "m"
)
phi <- matrix(</pre>
  data = c(
    -6, 5.5, 0, 0,
    1.25, -2.5, 5.9, -7.3,
    0, 0, -6, 2.5,
    5, 0, 0, -6
  ),
  nrow = 4
```

DirectStd 57

```
)
colnames(phi) <- rownames(phi) <- paste0("y", 1:4)
Direct(
   phi = phi,
   delta_t = delta_t,
   from = "y2",
   to = "y4",
   med = c("y1", "y3")
)</pre>
```

DirectStd

Standardized Direct Effect of X on Y Over a Specific Time Interval

## **Description**

This function computes the standardized direct effect of the independent variable X on the dependent variable Y through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  using the first-order stochastic differential equation model's drift matrix  $\mathbf{\Phi}$  and process noise covariance matrix  $\mathbf{\Sigma}$ .

# Usage

```
DirectStd(phi, sigma, delta_t, from, to, med)
```

## **Arguments**

phi	Numeric matrix. The drift matrix $(\Phi)$ , phi should have row and column names pertaining to the variables in the system.
sigma	Numeric matrix. The process noise covariance matrix $(\Sigma)$ .
delta_t	Numeric. Time interval ( $\Delta t$ ).
from	Character string. Name of the independent variable $X$ in $\mathtt{phi}$ .
to	Character string. Name of the dependent variable $Y$ in phi.
med	Character vector. Name/s of the mediator variable/s in phi.

## **Details**

The standardized direct effect of the independent variable X on the dependent variable Y relative to some mediator variables  $\mathbf{m}$  is given by

$$\operatorname{Direct}_{\Delta t_{i,j}}^* = \mathbf{S} \left( \exp \left( \Delta t \mathbf{D} \mathbf{\Phi} \mathbf{D} \right)_{i,j} \right) \mathbf{S}^{-1}$$

where  $\Phi$  denotes the drift matrix,  $\mathbf{D}$  a diagonal matrix where the diagonal elements corresponding to mediator variables  $\mathbf{m}$  are set to zero and the rest to one, i the row index of Y in  $\Phi$ , j the column index of X in  $\Phi$ ,  $\mathbf{S}$  a diagonal matrix with model-implied standard deviations on the diagonals, and  $\Delta t$  the time interval.

58 DirectStd

#### Value

Returns an object of class ctmedeffect which is a list with the following elements:

```
call Function call.args Function arguments.fun Function used ("DirectStd").output The standardized direct effect.
```

#### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
sigma <- matrix(
  data = c(
    0.24455556, 0.02201587, -0.05004762,
    0.02201587, 0.07067800, 0.01539456,
    -0.05004762, 0.01539456, 0.07553061
),</pre>
```

ExpCov 59

```
nrow = 3
)
delta_t <- 1
DirectStd(
    phi = phi,
    sigma = sigma,
    delta_t = delta_t,
    from = "x",
    to = "y",
    med = "m"
)</pre>
```

ExpCov

Model-Implied State Covariance Matrix

### **Description**

The function returns the model-implied state covariance matrix for a particular time interval  $\Delta t$  given by

$$\operatorname{vec}\left(\operatorname{Cov}\left(\boldsymbol{\eta}\right)\right) = \left(\mathbf{J} - \boldsymbol{\beta}_{\Delta t} \otimes \boldsymbol{\beta}_{\Delta t}\right)^{-1} \operatorname{vec}\left(\boldsymbol{\Psi}_{\Delta t}\right)$$

where

$$\begin{split} \boldsymbol{\beta}_{\Delta t} &= \exp \left( \Delta t \boldsymbol{\Phi} \right), \\ \boldsymbol{\Psi}_{\Delta t} &= \boldsymbol{\Phi}^{\#} \left( \exp \left( \Delta t \boldsymbol{\Phi} \right) - \mathbf{J} \right) \operatorname{vec} \left( \boldsymbol{\Sigma} \right), \quad \text{and} \\ \boldsymbol{\Phi}^{\#} &= \left( \boldsymbol{\Phi} \otimes \mathbf{I} \right) + \left( \mathbf{I} \otimes \boldsymbol{\Phi} \right). \end{split}$$

Note that I and J are identity matrices.

#### Usage

```
ExpCov(phi, sigma, delta_t)
```

## **Arguments**

phi	Numeric matrix. The drift matrix $(\Phi)$ . phi should have row and column names
	pertaining to the variables in the system.
sigma	Numeric matrix. The process noise covariance matrix $(\Sigma)$ .
delta_t	Numeric. Time interval ( $\Delta t$ ).

#### **Details**

# **Linear Stochastic Differential Equation Model:**

The measurement model is given by

$$\mathbf{y}_{i,t} = oldsymbol{
u} + oldsymbol{\Lambda} oldsymbol{\eta}_{i,t} + oldsymbol{arepsilon}_{i,t}, \quad ext{with} \quad oldsymbol{arepsilon}_{i,t} \sim \mathcal{N}\left(\mathbf{0}, oldsymbol{\Theta}
ight)$$

where  $\mathbf{y}_{i,t}$ ,  $\boldsymbol{\eta}_{i,t}$ , and  $\boldsymbol{\varepsilon}_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\boldsymbol{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\boldsymbol{\eta}_{i,t}$  a vector of latent random variables, and

 $\varepsilon_{i,t}$  a vector of random measurement errors, at time t and individual i.  $\nu$  denotes a vector of intercepts,  $\Lambda$  a matrix of factor loadings, and  $\Theta$  the covariance matrix of  $\varepsilon$ .

An alternative representation of the measurement error is given by

$$oldsymbol{arepsilon}_{i,t} = oldsymbol{\Theta}^{rac{1}{2}} \mathbf{z}_{i,t}, \quad ext{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}\left(\mathbf{0}, \mathbf{I}\right)$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $\left(\Theta^{\frac{1}{2}}\right)\left(\Theta^{\frac{1}{2}}\right)' = \Theta$ . The dynamic structure is given by

$$\mathrm{d} oldsymbol{\eta}_{i,t} = \left( oldsymbol{\iota} + oldsymbol{\Phi} oldsymbol{\eta}_{i,t} 
ight) \mathrm{d} t + oldsymbol{\Sigma}^{rac{1}{2}} \mathrm{d} \mathbf{W}_{i,t}$$

where  $\iota$  is a term which is unobserved and constant over time,  $\Phi$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\Sigma$  is the matrix of volatility or randomness in the process, and  $\mathrm{d} W$  is a Wiener process or Brownian motion, which represents random fluctuations.

#### Value

Returns a numeric matrix.

#### Author(s)

Ivan Jacob Agaloos Pesigan

### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
sigma <- matrix(
  data = c(
    0.24, 0.02, -0.05,
    0.02, 0.07, 0.02,
    -0.05, 0.02, 0.08</pre>
```

ExpMean 61

```
),
nrow = 3
)
delta_t <- 1
ExpCov(
phi = phi,
sigma = sigma,
delta_t = delta_t
)
```

ExpMean

Model-Implied State Mean Vector

## **Description**

The function returns the model-implied state mean vector for a particular time interval  $\Delta t$  given by

$$\operatorname{Mean}(\boldsymbol{\eta}) = (\mathbf{I} - \boldsymbol{\beta}_{\Delta t})^{-1} \boldsymbol{\alpha}_{\Delta t}$$

where

$$eta_{\Delta t} = \exp\left(\Delta t \mathbf{\Phi}\right),$$
  $oldsymbol{lpha}_{\Delta t} = \mathbf{\Phi}^{-1} \left(oldsymbol{eta}_{\Delta t} - \mathbf{I}\right) oldsymbol{\iota}.$ 

Note that I is an identity matrix.

#### **Usage**

```
ExpMean(phi, iota, delta_t)
```

# **Arguments**

phi	Numeric matrix. The drift matrix $(\Phi)$ , phi should have row and column names pertaining to the variables in the system.
iota	Numeric vector. An unobserved term that is constant over time ( $\iota$ ).
delta_t	Numeric. Time interval $(\Delta t)$ .

### **Details**

# **Linear Stochastic Differential Equation Model:**

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{
u} + \boldsymbol{\Lambda} \boldsymbol{\eta}_{i.t} + \boldsymbol{arepsilon}_{i,t}, \quad ext{with} \quad \boldsymbol{arepsilon}_{i,t} \sim \mathcal{N}\left(\mathbf{0}, \mathbf{\Theta}
ight)$$

where  $\mathbf{y}_{i,t}$ ,  $\eta_{i,t}$ , and  $\varepsilon_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\boldsymbol{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\eta_{i,t}$  a vector of latent random variables, and  $\varepsilon_{i,t}$  a vector of random measurement errors, at time t and individual i.  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\boldsymbol{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\varepsilon$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}} \mathbf{z}_{i,t}, \quad \text{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}\left(\mathbf{0}, \mathbf{I}\right)$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $\left(\boldsymbol{\Theta}^{\frac{1}{2}}\right)\left(\boldsymbol{\Theta}^{\frac{1}{2}}\right)' = \boldsymbol{\Theta}$ . The dynamic structure is given by

$$\mathrm{d}oldsymbol{\eta}_{i,t} = \left(oldsymbol{\iota} + oldsymbol{\Phi}oldsymbol{\eta}_{i,t}
ight)\mathrm{d}t + oldsymbol{\Sigma}^{rac{1}{2}}\mathrm{d}\mathbf{W}_{i,t}$$

where  $\iota$  is a term which is unobserved and constant over time,  $\Phi$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\Sigma$  is the matrix of volatility or randomness in the process, and  $\mathrm{d}W$  is a Wiener process or Brownian motion, which represents random fluctuations.

#### Value

Returns a numeric matrix.

## Author(s)

Ivan Jacob Agaloos Pesigan

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
iota <- c(.5, .3, .4)
delta_t <- 1
ExpMean(
  phi = phi,
  iota = iota,
  delta_t = delta_t
)</pre>
```

Indirect 63

Indirect

Indirect Effect of X on Y Through M Over a Specific Time Interval

## **Description**

This function computes the indirect effect of the independent variable X on the dependent variable Y through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  using the first-order stochastic differential equation model's drift matrix  $\mathbf{\Phi}$ .

#### Usage

Indirect(phi, delta\_t, from, to, med)

### **Arguments**

phi	Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system.
delta_t	Numeric. Time interval ( $\Delta t$ ).
from	Character string. Name of the independent variable $X$ in $\mathtt{phi}$ .
to	Character string. Name of the dependent variable $Y$ in phi.
med	Character vector. Name/s of the mediator variable/s in phi.

## **Details**

The indirect effect of the independent variable X on the dependent variable Y relative to some mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  is given by

Indirect<sub>$$\Delta t_{i,j}$$</sub> = exp  $(\Delta t \mathbf{\Phi})_{i,j}$  - exp  $(\Delta t \mathbf{D_m} \mathbf{\Phi} \mathbf{D_m})_{i,j}$ 

where  $\Phi$  denotes the drift matrix,  $\mathbf{D_m}$  a matrix where the off diagonal elements are zeros and the diagonal elements are zero for the index/indices of mediator variables  $\mathbf{m}$  and one otherwise, i the row index of Y in  $\Phi$ , j the column index of X in  $\Phi$ , and  $\Delta t$  the time interval.

## **Linear Stochastic Differential Equation Model:**

The measurement model is given by

$$\mathbf{y}_{i,t} = oldsymbol{
u} + oldsymbol{\Lambda} oldsymbol{\eta}_{i,t} + oldsymbol{arepsilon}_{i,t}, \quad ext{with} \quad oldsymbol{arepsilon}_{i,t} \sim \mathcal{N}\left(\mathbf{0}, oldsymbol{\Theta}
ight)$$

where  $\mathbf{y}_{i,t}$ ,  $\eta_{i,t}$ , and  $\varepsilon_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\boldsymbol{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\eta_{i,t}$  a vector of latent random variables, and  $\varepsilon_{i,t}$  a vector of random measurement errors, at time t and individual i.  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\boldsymbol{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\varepsilon$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}} \mathbf{z}_{i,t}, \quad \text{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}\left(\mathbf{0}, \mathbf{I}\right)$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $\left(\mathbf{\Theta}^{\frac{1}{2}}\right)\left(\mathbf{\Theta}^{\frac{1}{2}}\right)' = \mathbf{\Theta}$ .

64 Indirect

The dynamic structure is given by

$$\mathrm{d}\boldsymbol{\eta}_{i,t} = \left(\boldsymbol{\iota} + \boldsymbol{\Phi}\boldsymbol{\eta}_{i,t}\right) \mathrm{d}t + \boldsymbol{\Sigma}^{\frac{1}{2}} \mathrm{d}\mathbf{W}_{i,t}$$

where  $\iota$  is a term which is unobserved and constant over time,  $\Phi$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\Sigma$  is the matrix of volatility or randomness in the process, and  $\mathrm{d}W$  is a Wiener process or Brownian motion, which represents random fluctuations.

#### Value

Returns an object of class ctmedeffect which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("Indirect").

output The indirect effect.

#### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693</pre>
```

IndirectCentral 65

```
),
 nrow = 3
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
delta_t <- 1
Indirect(
  phi = phi,
 delta_t = delta_t,
  from = "x",
 to = "y",
  med = "m"
)
phi <- matrix(</pre>
  data = c(
    -6, 5.5, 0, 0,
   1.25, -2.5, 5.9, -7.3,
   0, 0, -6, 2.5,
   5, 0, 0, -6
 ),
 nrow = 4
)
colnames(phi) <- rownames(phi) <- paste0("y", 1:4)</pre>
Indirect(
  phi = phi,
  delta_t = delta_t,
 from = "y2",
  to = "y4",
  med = c("y1", "y3")
)
```

IndirectCentral

Indirect Effect Centrality

# Description

**Indirect Effect Centrality** 

# Usage

```
IndirectCentral(phi, delta_t, tol = 0.01)
```

# **Arguments**

phi	Numeric matrix. The drift matrix $(\Phi)$ , phi should have row and column names pertaining to the variables in the system.
delta_t	Vector of positive numbers. Time interval $(\Delta t)$ .
tol	Numeric. Smallest possible time interval to allow.

66 IndirectCentral

#### **Details**

Indirect effect centrality is the sum of all possible indirect effects between different pairs of variables in which a specific variable serves as the only mediator.

#### Value

Returns an object of class ctmedmed which is a list with the following elements:

```
call Function call.args Function arguments.fun Function used ("IndirectCentral").output A matrix of indirect effect centrality.
```

### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

# See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

IndirectStd 67

```
IndirectCentral(
 phi = phi,
 delta_t = 1
)
# Range of time intervals ------
indirect_central <- IndirectCentral(</pre>
 phi = phi,
 delta_t = 1:30
)
plot(indirect_central)
# Methods -----
# IndirectCentral has a number of methods including
# print, summary, and plot
indirect_central <- IndirectCentral(</pre>
 phi = phi,
 delta_t = 1:5
)
print(indirect_central)
summary(indirect_central)
plot(indirect_central)
```

IndirectStd

Standardized Indirect Effect of X on Y Through M Over a Specific Time Interval

# Description

This function computes the standardized indirect effect of the independent variable X on the dependent variable Y through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  using the first-order stochastic differential equation model's drift matrix  $\mathbf{\Phi}$  and process noise covariance matrix  $\mathbf{\Sigma}$ .

# Usage

```
IndirectStd(phi, sigma, delta_t, from, to, med)
```

# Arguments

phi	Numeric matrix. The drift matrix $(\Phi)$ . phi should have row and column names pertaining to the variables in the system.
sigma	Numeric matrix. The process noise covariance matrix $(\Sigma)$ .
delta_t	Numeric. Time interval ( $\Delta t$ ).
from	Character string. Name of the independent variable $X$ in phi.
to	Character string. Name of the dependent variable $Y$ in phi.
med	Character vector. Name/s of the mediator variable/s in phi.

68 IndirectStd

#### **Details**

The standardized indirect effect of the independent variable X on the dependent variable Y relative to some mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  is given by

$$Indirect^*_{\Delta t_{i,j}} = Total^*_{\Delta t} - Direct^*_{\Delta t}$$

where  $\operatorname{Total}_{\Delta t}^*$  and  $\operatorname{Direct}_{\Delta t}^*$  are standardized total and direct effects for time interval  $\Delta t$ .

#### Value

Returns an object of class ctmedeffect which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("IndirectStd").

output The standardized indirect effect.

## Author(s)

Ivan Jacob Agaloos Pesigan

### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

## See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
),</pre>
```

MCBeta 69

```
nrow = 3
colnames(phi) \leftarrow rownames(phi) \leftarrow c("x", "m", "y")
sigma <- matrix(</pre>
  data = c(
    0.24455556, 0.02201587, -0.05004762,
    0.02201587, 0.07067800, 0.01539456,
    -0.05004762, 0.01539456, 0.07553061
  ),
  nrow = 3
)
delta_t <- 1
IndirectStd(
  phi = phi,
  sigma = sigma,
  delta_t = delta_t,
  from = "x",
  to = "y",
  med = "m"
```

MCBeta

Monte Carlo Sampling Distribution for the Elements of the Matrix of Lagged Coefficients Over a Specific Time Interval or a Range of Time Intervals

# Description

This function generates a Monte Carlo method sampling distribution for the elements of the matrix of lagged coefficients  $\beta$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model drift matrix  $\Phi$ .

# Usage

```
MCBeta(
   phi,
   vcov_phi_vec,
   delta_t,
   R,
   test_phi = TRUE,
   ncores = NULL,
   seed = NULL,
   tol = 0.01
)
```

70 MCBeta

## Arguments

phi Numeric matrix. The drift matrix ( $\Phi$ ), phi should have row and column names

pertaining to the variables in the system.

vcov\_phi\_vec Numeric matrix. The sampling variance-covariance matrix of vec  $(\Phi)$ .

delta\_t Numeric. Time interval ( $\Delta t$ ).

R Positive integer. Number of replications.

test\_phi Logical. If test\_phi = TRUE, the function tests the stability of the generated

drift matrix  $\Phi$ . If the test returns FALSE, the function generates a new drift

matrix  $\Phi$  and runs the test recursively until the test returns TRUE.

ncores Positive integer. Number of cores to use. If ncores = NULL, use a single core.

Consider using multiple cores when number of replications R is a large value.

seed Random seed.

tol Numeric. Smallest possible time interval to allow.

### **Details**

See Total().

#### **Monte Carlo Method:**

Let  $\theta$  be  $\operatorname{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be  $\operatorname{vec}(\hat{\Phi})$ . Based on the asymptotic properties of maximum likelihood estimators, we can assume that estimators are normally distributed around the population parameters.

$$\hat{oldsymbol{ heta}} \sim \mathcal{N}\left(oldsymbol{ heta}, \mathbb{V}\left(\hat{oldsymbol{ heta}}
ight)
ight)$$

Using this distributional assumption, a sampling distribution of  $\hat{\theta}$  which we refer to as  $\hat{\theta}^*$  can be generated by replacing the population parameters with sample estimates, that is,

$$\hat{oldsymbol{ heta}}^* \sim \mathcal{N}\left(\hat{oldsymbol{ heta}}, \hat{\mathbb{V}}\left(\hat{oldsymbol{ heta}}
ight)
ight).$$

Let  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  be a parameter that is a function of the estimated parameters. A sampling distribution of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$ , which we refer to as  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}^*\right)$ , can be generated by using the simulated estimates to calculate  $\mathbf{g}$ . The standard deviations of the simulated estimates are the standard errors. Percentiles corresponding to  $100\left(1-\alpha\right)\%$  are the confidence intervals.

### Value

Returns an object of class ctmedmc which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("MCBeta").

output A list the length of which is equal to the length of delta\_t.

Each element in the output list has the following elements:

**est** Estimated elements of the matrix of lagged coefficients.

thetahatstar A matrix of Monte Carlo elements of the matrix of lagged coefficients.

MCBeta 71

### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

```
set.seed(42)
phi <- matrix(</pre>
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) \leftarrow rownames(phi) \leftarrow c("x", "m", "y")
vcov_phi_vec <- matrix(</pre>
  data = c(
    0.00843, 0.00040, -0.00151,
    -0.00600, -0.00033, 0.00110,
    0.00324, 0.00020, -0.00061,
    0.00040, 0.00374, 0.00016,
    -0.00022, -0.00273, -0.00016,
    0.00009, 0.00150, 0.00012,
    -0.00151, 0.00016, 0.00389,
    0.00103, -0.00007, -0.00283,
    -0.00050, 0.00000, 0.00156,
    -0.00600, -0.00022, 0.00103,
    0.00644, 0.00031, -0.00119,
    -0.00374, -0.00021, 0.00070,
    -0.00033, -0.00273, -0.00007,
```

72 MCBetaStd

```
0.00031, 0.00287, 0.00013,
   -0.00014, -0.00170, -0.00012,
   0.00110, -0.00016, -0.00283,
   -0.00119, 0.00013, 0.00297,
   0.00063, -0.00004, -0.00177,
   0.00324, 0.00009, -0.00050,
   -0.00374, -0.00014, 0.00063,
   0.00495, 0.00024, -0.00093,
   0.00020, 0.00150, 0.00000,
   -0.00021, -0.00170, -0.00004,
   0.00024, 0.00214, 0.00012,
   -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
   -0.00093, 0.00012, 0.00223
 ),
 nrow = 9
)
# Specific time interval ------
MCBeta(
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1,
 R = 100L # use a large value for R in actual research
)
# Range of time intervals ------
mc <- MCBeta(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1:5,
 R = 100L # use a large value for R in actual research
plot(mc)
# Methods ------
# MCBeta has a number of methods including
# print, summary, confint, and plot
print(mc)
summary(mc)
confint(mc, level = 0.95)
plot(mc)
```

MCBetaStd

Monte Carlo Sampling Distribution for the Elements of the Standardized Matrix of Lagged Coefficients Over a Specific Time Interval or a Range of Time Intervals MCBetaStd 73

## **Description**

This function generates a Monte Carlo method sampling distribution for the elements of the standardized matrix of lagged coefficients  $\beta$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model drift matrix  $\Phi$  and process noise covariance matrix  $\Sigma$ .

# Usage

```
MCBetaStd(
  phi,
  sigma,
  vcov_theta,
  delta_t,
  R,
  test_phi = TRUE,
  ncores = NULL,
  seed = NULL,
  tol = 0.01
)
```

# Arguments

phi	Numeric matrix. The drift matrix $(\Phi)$ , phi should have row and column names pertaining to the variables in the system.
sigma	Numeric matrix. The process noise covariance matrix $(\Sigma)$ .
vcov_theta	Numeric matrix. The sampling variance-covariance matrix of $\operatorname{vec}\left(\mathbf{\Phi}\right)$ and $\operatorname{vech}\left(\mathbf{\Sigma}\right)$
delta_t	Numeric. Time interval ( $\Delta t$ ).
R	Positive integer. Number of replications.
test_phi	Logical. If test_phi = TRUE, the function tests the stability of the generated drift matrix $\Phi$ . If the test returns FALSE, the function generates a new drift matrix $\Phi$ and runs the test recursively until the test returns TRUE.
ncores	Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.
seed	Random seed.
tol	Numeric. Smallest possible time interval to allow.

### **Details**

See TotalStd().

### **Monte Carlo Method:**

Let  $\theta$  be a vector that combines  $\operatorname{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise and  $\operatorname{vech}(\Sigma)$ , that is, the unique elements of the  $\Sigma$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be a vector that combines  $\operatorname{vec}(\hat{\Phi})$  and  $\operatorname{vech}(\hat{\Sigma})$ . Based on the

asymptotic properties of maximum likelihood estimators, we can assume that estimators are normally distributed around the population parameters.

$$\hat{oldsymbol{ heta}} \sim \mathcal{N}\left(oldsymbol{ heta}, \mathbb{V}\left(\hat{oldsymbol{ heta}}
ight)
ight)$$

Using this distributional assumption, a sampling distribution of  $\hat{\theta}$  which we refer to as  $\hat{\theta}^*$  can be generated by replacing the population parameters with sample estimates, that is,

$$\hat{oldsymbol{ heta}}^* \sim \mathcal{N}\left(\hat{oldsymbol{ heta}}, \hat{\mathbb{V}}\left(\hat{oldsymbol{ heta}}
ight)
ight).$$

Let  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  be a parameter that is a function of the estimated parameters. A sampling distribution of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$ , which we refer to as  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}^*\right)$ , can be generated by using the simulated estimates to calculate  $\mathbf{g}$ . The standard deviations of the simulated estimates are the standard errors. Percentiles corresponding to  $100\left(1-\alpha\right)\%$  are the confidence intervals.

#### Value

Returns an object of class ctmedmc which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("MCBetaStd").

**output** A list the length of which is equal to the length of delta\_t.

Each element in the output list has the following elements:

est Estimated elements of the standardized matrix of lagged coefficients.

thetahatstar A matrix of Monte Carlo elements of the standardized matrix of lagged coefficients.

## Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

MCBetaStd 75

#### See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

```
phi <- matrix(</pre>
 data = c(
   -0.357, 0.771, -0.450,
   0.0, -0.511, 0.729,
   0, 0, -0.693
 ),
 nrow = 3
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
sigma <- matrix(</pre>
 data = c(
   0.24455556, 0.02201587, -0.05004762,
   0.02201587, 0.07067800, 0.01539456,
   -0.05004762, 0.01539456, 0.07553061
 ),
 nrow = 3
)
vcov_theta <- matrix(</pre>
 data = c(
    0.00843, 0.00040, -0.00151, -0.00600, -0.00033,
   0.00110, 0.00324, 0.00020, -0.00061, -0.00115,
    0.00011, 0.00015, 0.00001, -0.00002, -0.00001,
   0.00040, 0.00374, 0.00016, -0.00022, -0.00273,
   -0.00016, 0.00009, 0.00150, 0.00012, -0.00010,
   -0.00026, 0.00002, 0.00012, 0.00004, -0.00001,
   -0.00151, 0.00016, 0.00389, 0.00103, -0.00007,
   -0.00283, -0.00050, 0.00000, 0.00156, 0.00021,
   -0.00005, -0.00031, 0.00001, 0.00007, 0.00006,
   -0.00600, -0.00022, 0.00103, 0.00644, 0.00031,
   -0.00119, -0.00374, -0.00021, 0.00070, 0.00064,
   -0.00015, -0.00005, 0.00000, 0.00003, -0.00001,
   -0.00033, -0.00273, -0.00007, 0.00031, 0.00287,
   0.00013, -0.00014, -0.00170, -0.00012, 0.00006,
    0.00014, -0.00001, -0.00015, 0.00000, 0.00001,
    0.00110, -0.00016, -0.00283, -0.00119, 0.00013,
   0.00297, 0.00063, -0.00004, -0.00177, -0.00013,
   0.00005, 0.00017, -0.00002, -0.00008, 0.00001,
   0.00324, 0.00009, -0.00050, -0.00374, -0.00014,
   0.00063, 0.00495, 0.00024, -0.00093, -0.00020,
   0.00006, -0.00010, 0.00000, -0.00001, 0.00004,
```

76 MCBetaStd

```
0.00020, 0.00150, 0.00000, -0.00021, -0.00170,
   -0.00004, 0.00024, 0.00214, 0.00012, -0.00002,
   -0.00004, 0.00000, 0.00006, -0.00005, -0.00001,
   -0.00061, 0.00012, 0.00156, 0.00070, -0.00012,
   -0.00177, -0.00093, 0.00012, 0.00223, 0.00004,
   -0.00002, -0.00003, 0.00001, 0.00003, -0.00013,
   -0.00115, -0.00010, 0.00021, 0.00064, 0.00006,
   -0.00013, -0.00020, -0.00002, 0.00004, 0.00057,
   0.00001, -0.00009, 0.00000, 0.00000, 0.00001,
   0.00011, -0.00026, -0.00005, -0.00015, 0.00014,
   0.00005, 0.00006, -0.00004, -0.00002, 0.00001,
   0.00012, 0.00001, 0.00000, -0.00002, 0.00000,
   0.00015, 0.00002, -0.00031, -0.00005, -0.00001,
   0.00017, -0.00010, 0.00000, -0.00003, -0.00009,
   0.00001, 0.00014, 0.00000, 0.00000, -0.00005,
   0.00001, 0.00012, 0.00001, 0.00000, -0.00015,
   -0.00002, 0.00000, 0.00006, 0.00001, 0.00000,
   0.00000, 0.00000, 0.00010, 0.00001, 0.00000,
   -0.00002, 0.00004, 0.00007, 0.00003, 0.00000,
   -0.00008, -0.00001, -0.00005, 0.00003, 0.00000,
   -0.00002, 0.00000, 0.00001, 0.00005, 0.00001,
   -0.00001, -0.00001, 0.00006, -0.00001, 0.00001,
   0.00001, 0.00004, -0.00001, -0.00013, 0.00001,
   0.00000, -0.00005, 0.00000, 0.00001, 0.00012
 ),
 nrow = 15
)
# Specific time interval -------
MCBetaStd(
 phi = phi,
 sigma = sigma,
 vcov_theta = vcov_theta,
 delta_t = 1,
 R = 100L # use a large value for R in actual research
)
# Range of time intervals ------
mc <- MCBetaStd(</pre>
 phi = phi,
 sigma = sigma,
 vcov_theta = vcov_theta,
 delta_t = 1:5,
 R = 100L # use a large value for R in actual research
)
plot(mc)
# Methods ------
# MCBetaStd has a number of methods including
# print, summary, confint, and plot
print(mc)
summary(mc)
confint(mc, level = 0.95)
```

MCIndirectCentral 77

```
plot(mc)
```

MCIndirectCentral

Monte Carlo Sampling Distribution of Indirect Effect Centrality Over a Specific Time Interval or a Range of Time Intervals

# Description

This function generates a Monte Carlo method sampling distribution of the indirect effect centrality at a particular time interval  $\Delta t$  using the first-order stochastic differential equation model drift matrix  $\Phi$ .

# Usage

```
MCIndirectCentral(
  phi,
  vcov_phi_vec,
  delta_t,
  R,
  test_phi = TRUE,
  ncores = NULL,
  seed = NULL,
  tol = 0.01
)
```

### **Arguments**

phi	Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system.
vcov_phi_vec	Numeric matrix. The sampling variance-covariance matrix of $\operatorname{vec}\left(\mathbf{\Phi}\right)$ .
delta_t	Numeric. Time interval ( $\Delta t$ ).
R	Positive integer. Number of replications.
test_phi	Logical. If test_phi = TRUE, the function tests the stability of the generated drift matrix $\Phi$ . If the test returns FALSE, the function generates a new drift matrix $\Phi$ and runs the test recursively until the test returns TRUE.
ncores	Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.
seed	Random seed.
tol	Numeric. Smallest possible time interval to allow.

#### **Details**

See IndirectCentral() for more details.

#### **Monte Carlo Method:**

Let  $\theta$  be  $\operatorname{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be  $\operatorname{vec}(\hat{\Phi})$ . Based on the asymptotic properties of maximum likelihood estimators, we can assume that estimators are normally distributed around the population parameters.

$$\hat{oldsymbol{ heta}} \sim \mathcal{N}\left(oldsymbol{ heta}, \mathbb{V}\left(\hat{oldsymbol{ heta}}
ight)
ight)$$

Using this distributional assumption, a sampling distribution of  $\hat{\theta}$  which we refer to as  $\hat{\theta}^*$  can be generated by replacing the population parameters with sample estimates, that is,

$$\hat{oldsymbol{ heta}}^* \sim \mathcal{N}\left(\hat{oldsymbol{ heta}}, \hat{\mathbb{V}}\left(\hat{oldsymbol{ heta}}
ight)
ight).$$

Let  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  be a parameter that is a function of the estimated parameters. A sampling distribution of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$ , which we refer to as  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}^*\right)$ , can be generated by using the simulated estimates to calculate  $\mathbf{g}$ . The standard deviations of the simulated estimates are the standard errors. Percentiles corresponding to  $100\left(1-\alpha\right)\%$  are the confidence intervals.

#### Value

Returns an object of class ctmedmc which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("MCIndirectCentral").

**output** A list the length of which is equal to the length of delta\_t.

Each element in the output list has the following elements:

est A vector of indirect effect centrality.

thetahatstar A matrix of Monte Carlo indirect effect centrality.

# Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

MCIndirectCentral 79

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
set.seed(42)
phi <- matrix(</pre>
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
   0, 0, -0.693
  ),
  nrow = 3
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
vcov_phi_vec <- matrix(</pre>
  data = c(
    0.00843, 0.00040, -0.00151,
    -0.00600, -0.00033, 0.00110,
    0.00324, 0.00020, -0.00061,
    0.00040, 0.00374, 0.00016,
    -0.00022, -0.00273, -0.00016,
    0.00009, 0.00150, 0.00012,
    -0.00151, 0.00016, 0.00389,
    0.00103, -0.00007, -0.00283,
    -0.00050, 0.00000, 0.00156,
    -0.00600, -0.00022, 0.00103,
    0.00644, 0.00031, -0.00119,
    -0.00374, -0.00021, 0.00070,
    -0.00033, -0.00273, -0.00007,
    0.00031, 0.00287, 0.00013,
    -0.00014, -0.00170, -0.00012,
    0.00110, -0.00016, -0.00283,
    -0.00119, 0.00013, 0.00297,
    0.00063, -0.00004, -0.00177,
    0.00324, 0.00009, -0.00050,
    -0.00374, -0.00014, 0.00063,
    0.00495, 0.00024, -0.00093,
    0.00020, 0.00150, 0.00000,
    -0.00021, -0.00170, -0.00004,
    0.00024, 0.00214, 0.00012,
    -0.00061, 0.00012, 0.00156,
    0.00070, -0.00012, -0.00177,
    -0.00093, 0.00012, 0.00223
  ),
  nrow = 9
)
```

80 MCMed

```
# Specific time interval ------
MCIndirectCentral(
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1,
 R = 100L # use a large value for R in actual research
# Range of time intervals -----
mc <- MCIndirectCentral(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1:5,
 R = 100L # use a large value for R in actual research
)
plot(mc)
# Methods -----
# MCIndirectCentral has a number of methods including
# print, summary, confint, and plot
print(mc)
summary(mc)
confint(mc, level = 0.95)
plot(mc)
```

MCMed

Monte Carlo Sampling Distribution of Total, Direct, and Indirect Effects of X on Y Through M Over a Specific Time Interval or a Range of Time Intervals

# **Description**

This function generates a Monte Carlo method sampling distribution of the total, direct and indirect effects of the independent variable X on the dependent variable Y through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model drift matrix  $\mathbf{\Phi}$ .

# Usage

```
MCMed(
   phi,
   vcov_phi_vec,
   delta_t,
   from,
   to,
   med,
   R,
```

MCMed 81

```
test_phi = TRUE,
ncores = NULL,
seed = NULL,
tol = 0.01
)
```

#### **Arguments**

phi Numeric matrix. The drift matrix ( $\Phi$ ), phi should have row and column names

pertaining to the variables in the system.

vcov\_phi\_vec Numeric matrix. The sampling variance-covariance matrix of  $\operatorname{vec}\left(\Phi\right)$ .

delta\_t Numeric. Time interval ( $\Delta t$ ).

from Character string. Name of the independent variable X in phi.

to Character string. Name of the dependent variable Y in phi.

med Character vector. Name/s of the mediator variable/s in phi.

R Positive integer. Number of replications.

test\_phi Logical. If test\_phi = TRUE, the function tests the stability of the generated

drift matrix  $\Phi$ . If the test returns FALSE, the function generates a new drift

matrix  $\Phi$  and runs the test recursively until the test returns TRUE.

ncores Positive integer. Number of cores to use. If ncores = NULL, use a single core.

Consider using multiple cores when number of replications R is a large value.

seed Random seed.

tol Numeric. Smallest possible time interval to allow.

### **Details**

See Total(), Direct(), and Indirect() for more details.

#### **Monte Carlo Method:**

Let  $\theta$  be  $\operatorname{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be  $\operatorname{vec}(\hat{\Phi})$ . Based on the asymptotic properties of maximum likelihood estimators, we can assume that estimators are normally distributed around the population parameters.

$$\hat{oldsymbol{ heta}} \sim \mathcal{N}\left(oldsymbol{ heta}, \mathbb{V}\left(\hat{oldsymbol{ heta}}
ight)
ight)$$

Using this distributional assumption, a sampling distribution of  $\hat{\theta}$  which we refer to as  $\hat{\theta}^*$  can be generated by replacing the population parameters with sample estimates, that is,

$$\hat{\boldsymbol{\theta}}^* \sim \mathcal{N}\left(\hat{\boldsymbol{\theta}}, \hat{\mathbb{V}}\left(\hat{\boldsymbol{\theta}}\right)\right).$$

Let  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  be a parameter that is a function of the estimated parameters. A sampling distribution of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$ , which we refer to as  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}^*\right)$ , can be generated by using the simulated estimates to calculate  $\mathbf{g}$ . The standard deviations of the simulated estimates are the standard errors. Percentiles corresponding to  $100\left(1-\alpha\right)\%$  are the confidence intervals.

MCMed MCMed

#### Value

Returns an object of class ctmedmc which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("MCMed").

output A list with length of length(delta\_t).

Each element in the output list has the following elements:

est A vector of total, direct, and indirect effects.

thetahatstar A matrix of Monte Carlo total, direct, and indirect effects.

#### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

```
set.seed(42)
phi <- matrix(
   data = c(
     -0.357, 0.771, -0.450,
     0.0, -0.511, 0.729,
     0, 0, -0.693
   ),
   nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
```

MCMed 83

```
vcov_phi_vec <- matrix(</pre>
 data = c(
   0.00843, 0.00040, -0.00151,
   -0.00600, -0.00033, 0.00110,
   0.00324, 0.00020, -0.00061,
   0.00040, 0.00374, 0.00016,
   -0.00022, -0.00273, -0.00016,
   0.00009, 0.00150, 0.00012,
   -0.00151, 0.00016, 0.00389,
   0.00103, -0.00007, -0.00283,
   -0.00050, 0.00000, 0.00156,
   -0.00600, -0.00022, 0.00103,
   0.00644, 0.00031, -0.00119,
   -0.00374, -0.00021, 0.00070,
   -0.00033, -0.00273, -0.00007,
   0.00031, 0.00287, 0.00013,
   -0.00014, -0.00170, -0.00012,
   0.00110, -0.00016, -0.00283,
   -0.00119, 0.00013, 0.00297,
   0.00063, -0.00004, -0.00177,
   0.00324, 0.00009, -0.00050,
   -0.00374, -0.00014, 0.00063,
   0.00495, 0.00024, -0.00093,
   0.00020, 0.00150, 0.00000,
   -0.00021, -0.00170, -0.00004,
   0.00024, 0.00214, 0.00012,
   -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
   -0.00093, 0.00012, 0.00223
 ),
 nrow = 9
)
# Specific time interval -------
MCMed(
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1,
 from = "x",
 to = "y",
 med = "m"
 R = 100L # use a large value for R in actual research
)
# Range of time intervals ------
mc <- MCMed(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1:5,
 from = "x",
 to = "y",
 med = "m"
 R = 100L # use a large value for R in actual research
```

```
plot(mc)

# Methods ------

# MCMed has a number of methods including

# print, summary, confint, and plot
print(mc)
summary(mc)
confint(mc, level = 0.95)
```

MCMedStd

Monte Carlo Sampling Distribution of Standardized Total, Direct, and Indirect Effects of X on Y Through M Over a Specific Time Interval or a Range of Time Intervals

# **Description**

This function generates a Monte Carlo method sampling distribution of the standardized total, direct and indirect effects of the independent variable X on the dependent variable Y through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model drift matrix  $\mathbf{\Phi}$  and process noise covariance matrix  $\mathbf{\Sigma}$ .

## Usage

```
MCMedStd(
   phi,
   sigma,
   vcov_theta,
   delta_t,
   from,
   to,
   med,
   R,
   test_phi = TRUE,
   ncores = NULL,
   seed = NULL,
   tol = 0.01
)
```

# **Arguments**

delta\_t

phi	Numeric matrix. The drift matrix $(\Phi)$ . phi should have row and column names
	pertaining to the variables in the system.
sigma	Numeric matrix. The process noise covariance matrix $(\Sigma)$ .
vcov_theta	Numeric matrix. The sampling variance-covariance matrix of $\operatorname{vec}\left(\mathbf{\Phi}\right)$ and $\operatorname{vech}\left(\mathbf{\Sigma}\right)$

Numeric. Time interval ( $\Delta t$ ).

from Character string. Name of the independent variable X in phi. to Character string. Name of the dependent variable Y in phi. med Character vector. Name/s of the mediator variable/s in phi. Positive integer. Number of replications. R test\_phi Logical. If test\_phi = TRUE, the function tests the stability of the generated drift matrix  $\Phi$ . If the test returns FALSE, the function generates a new drift matrix  $\Phi$  and runs the test recursively until the test returns TRUE. ncores Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value. Random seed. seed

Numeric. Smallest possible time interval to allow. tol

#### **Details**

See TotalStd(), DirectStd(), and IndirectStd() for more details.

#### **Monte Carlo Method:**

Let  $\theta$  be a vector that combines vec  $(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise and vech  $(\Sigma)$ , that is, the unique elements of the  $\Sigma$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be a vector that combines  $\operatorname{vec}\left(\hat{\Phi}\right)$  and  $\operatorname{vech}\left(\hat{\Sigma}\right)$ . Based on the asymptotic properties of maximum likelihood estimators, we can assume that estimators are normally distributed around the population parameters

$$\hat{oldsymbol{ heta}} \sim \mathcal{N}\left(oldsymbol{ heta}, \mathbb{V}\left(\hat{oldsymbol{ heta}}
ight)
ight)$$

Using this distributional assumption, a sampling distribution of  $\hat{\theta}$  which we refer to as  $\hat{\theta}^*$  can be generated by replacing the population parameters with sample estimates, that is,

$$\hat{oldsymbol{ heta}}^* \sim \mathcal{N}\left(\hat{oldsymbol{ heta}}, \hat{\mathbb{V}}\left(\hat{oldsymbol{ heta}}
ight)
ight).$$

Let  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  be a parameter that is a function of the estimated parameters. A sampling distribution of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  , which we refer to as  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}^*\right)$  , can be generated by using the simulated estimates to calculate g. The standard deviations of the simulated estimates are the standard errors. Percentiles corresponding to  $100 (1 - \alpha) \%$  are the confidence intervals.

### Value

Returns an object of class ctmedmc which is a list with the following elements:

**call** Function call.

args Function arguments.

fun Function used ("MCMedStd").

**output** A list with length of length(delta\_t).

Each element in the output list has the following elements:

**est** A vector of standardized total, direct, and indirect effects.

thetahatstar A matrix of Monte Carlo standardized total, direct, and indirect effects.

#### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), MCBetaStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

```
phi <- matrix(</pre>
 data = c(
   -0.357, 0.771, -0.450,
   0.0, -0.511, 0.729,
   0, 0, -0.693
 ),
 nrow = 3
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
sigma <- matrix(</pre>
 data = c(
   0.24455556, 0.02201587, -0.05004762,
   0.02201587, 0.07067800, 0.01539456,
    -0.05004762, 0.01539456, 0.07553061
 ),
 nrow = 3
)
vcov_theta <- matrix(</pre>
 data = c(
    0.00843, 0.00040, -0.00151, -0.00600, -0.00033,
    0.00110, 0.00324, 0.00020, -0.00061, -0.00115,
    0.00011, 0.00015, 0.00001, -0.00002, -0.00001,
    0.00040, 0.00374, 0.00016, -0.00022, -0.00273,
    -0.00016, 0.00009, 0.00150, 0.00012, -0.00010,
    -0.00026, 0.00002, 0.00012, 0.00004, -0.00001,
```

```
-0.00151, 0.00016, 0.00389, 0.00103, -0.00007,
    -0.00283, -0.00050, 0.00000, 0.00156, 0.00021,
   -0.00005, -0.00031, 0.00001, 0.00007, 0.00006,
   -0.00600, -0.00022, 0.00103, 0.00644, 0.00031,
   -0.00119, -0.00374, -0.00021, 0.00070, 0.00064,
   -0.00015, -0.00005, 0.00000, 0.00003, -0.00001,
    -0.00033, -0.00273, -0.00007, 0.00031, 0.00287,
   0.00013, -0.00014, -0.00170, -0.00012, 0.00006,
   0.00014, -0.00001, -0.00015, 0.00000, 0.00001,
   0.00110, -0.00016, -0.00283, -0.00119, 0.00013,
   0.00297, 0.00063, -0.00004, -0.00177, -0.00013,
   0.00005, 0.00017, -0.00002, -0.00008, 0.00001,
   0.00324, 0.00009, -0.00050, -0.00374, -0.00014,
    0.00063, 0.00495, 0.00024, -0.00093, -0.00020,
   0.00006, -0.00010, 0.00000, -0.00001, 0.00004,
   0.00020, 0.00150, 0.00000, -0.00021, -0.00170,
    -0.00004, 0.00024, 0.00214, 0.00012, -0.00002,
    -0.00004, 0.00000, 0.00006, -0.00005, -0.00001,
    -0.00061, 0.00012, 0.00156, 0.00070, -0.00012,
    -0.00177, -0.00093, 0.00012, 0.00223, 0.00004,
    -0.00002, -0.00003, 0.00001, 0.00003, -0.00013,
    -0.00115, -0.00010, 0.00021, 0.00064, 0.00006,
    -0.00013, -0.00020, -0.00002, 0.00004, 0.00057,
   0.00001, -0.00009, 0.00000, 0.00000, 0.00001,
   0.00011, -0.00026, -0.00005, -0.00015, 0.00014,
   0.00005, 0.00006, -0.00004, -0.00002, 0.00001,
    0.00012, 0.00001, 0.00000, -0.00002, 0.00000,
   0.00015, 0.00002, -0.00031, -0.00005, -0.00001,
   0.00017, -0.00010, 0.00000, -0.00003, -0.00009,
   0.00001, 0.00014, 0.00000, 0.00000, -0.00005,
   0.00001, 0.00012, 0.00001, 0.00000, -0.00015,
    -0.00002, 0.00000, 0.00006, 0.00001, 0.00000,
   0.00000, 0.00000, 0.00010, 0.00001, 0.00000,
    -0.00002, 0.00004, 0.00007, 0.00003, 0.00000,
    -0.00008, -0.00001, -0.00005, 0.00003, 0.00000,
   -0.00002, 0.00000, 0.00001, 0.00005, 0.00001,
    -0.00001, -0.00001, 0.00006, -0.00001, 0.00001,
   0.00001, 0.00004, -0.00001, -0.00013, 0.00001,
    0.00000, -0.00005, 0.00000, 0.00001, 0.00012
 ),
 nrow = 15
)
# Specific time interval -------
MCMedStd(
 phi = phi,
 sigma = sigma,
 vcov_theta = vcov_theta,
 delta_t = 1,
 from = "x",
 to = "y",
 med = "m"
 R = 100L # use a large value for R in actual research
```

88 MCPhi

```
)
# Range of time intervals ------
mc <- MCMedStd(</pre>
 phi = phi,
 sigma = sigma,
 vcov_theta = vcov_theta,
 delta_t = 1:5,
 from = "x",
 to = "y",
 med = "m",
 R = 100L \; \# \; use \; a \; large \; value \; for \; R \; in \; actual \; research
plot(mc)
# Methods -----
# MCMedStd has a number of methods including
# print, summary, confint, and plot
print(mc)
summary(mc)
confint(mc, level = 0.95)
```

MCPhi

Generate Random Drift Matrices Using the Monte Carlo Method

# Description

This function generates random drift matrices  $\Phi$  using the Monte Carlo method.

#### Usage

```
MCPhi(phi, vcov_phi_vec, R, test_phi = TRUE, ncores = NULL, seed = NULL)
```

# Arguments

phi	Numeric matrix. The drift matrix ( $\Phi$ ). phi should have row and column names pertaining to the variables in the system.
vcov_phi_vec	Numeric matrix. The sampling variance-covariance matrix of $\operatorname{vec}\left(\Phi\right)$ .
R	Positive integer. Number of replications.
test_phi	Logical. If test_phi = TRUE, the function tests the stability of the generated drift matrix $\Phi$ . If the test returns FALSE, the function generates a new drift matrix $\Phi$ and runs the test recursively until the test returns TRUE.
ncores	Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.
seed	Random seed.

MCPhi 89

#### **Details**

#### **Monte Carlo Method:**

Let  $\theta$  be  $\operatorname{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be  $\operatorname{vec}(\hat{\Phi})$ . Based on the asymptotic properties of maximum likelihood estimators, we can assume that estimators are normally distributed around the population parameters.

$$\hat{oldsymbol{ heta}} \sim \mathcal{N}\left(oldsymbol{ heta}, \mathbb{V}\left(\hat{oldsymbol{ heta}}
ight)
ight)$$

Using this distributional assumption, a sampling distribution of  $\hat{\theta}$  which we refer to as  $\hat{\theta}^*$  can be generated by replacing the population parameters with sample estimates, that is,

$$\hat{oldsymbol{ heta}}^* \sim \mathcal{N}\left(\hat{oldsymbol{ heta}}, \hat{\mathbb{V}}\left(\hat{oldsymbol{ heta}}
ight)
ight).$$

#### Value

Returns an object of class ctmedmc which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("MCPhi").

**output** A list simulated drift matrices.

#### Author(s)

Ivan Jacob Agaloos Pesigan

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
set.seed(42)
phi <- matrix(
   data = c(
     -0.357, 0.771, -0.450,
     0.0, -0.511, 0.729,
     0, 0, -0.693
   ),
   nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
```

90 **MCPhiSigma** 

```
MCPhi(
  phi = phi,
  vcov_phi_vec = 0.1 * diag(9),
  R = 100L # use a large value for R in actual research
)
phi <- matrix(</pre>
  data = c(
    -6, 5.5, 0, 0,
    1.25, -2.5, 5.9, -7.3,
    0, 0, -6, 2.5,
    5, 0, 0, -6
  ),
  nrow = 4
colnames(phi) <- rownames(phi) <- paste0("y", 1:4)</pre>
MCPhi(
  phi = phi,
  vcov_phi_vec = 0.1 * diag(16),
  R = 100L, # use a large value for R in actual research
  test_phi = FALSE
)
```

MCPhiSigma

Generate Random Drift Matrices and Process Noise Covariance Matrices Using the Monte Carlo Method

# Description

This function generates random drift matrices  $\Phi$  and process noise covariabces matrices  $\Sigma$  using the Monte Carlo method.

# Usage

```
MCPhiSigma(
  phi,
  sigma,
  vcov_theta,
  R,
  test_phi = TRUE,
  ncores = NULL,
  seed = NULL
)
```

### Arguments

phi Numeric matrix. The drift matrix  $(\Phi)$ . phi should have row and column names pertaining to the variables in the system.

Numeric matrix. The process noise covariance matrix  $(\Sigma)$ .

sigma

MCPhiSigma 91

vcov_theta	Numeric matrix. The sampling variance-covariance matrix of $\operatorname{vec}\left(\mathbf{\Phi}\right)$ and $\operatorname{vech}\left(\mathbf{\Sigma}\right)$
R	Positive integer. Number of replications.
test_phi	Logical. If test_phi = TRUE, the function tests the stability of the generated drift matrix $\Phi$ . If the test returns FALSE, the function generates a new drift matrix $\Phi$ and runs the test recursively until the test returns TRUE.
ncores	Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.
seed	Random seed.

#### **Details**

#### **Monte Carlo Method:**

Let  $\theta$  be a vector that combines  $\operatorname{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise and  $\operatorname{vech}(\Sigma)$ , that is, the unique elements of the  $\Sigma$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be a vector that combines  $\operatorname{vec}(\hat{\Phi})$  and  $\operatorname{vech}(\hat{\Sigma})$ . Based on the asymptotic properties of maximum likelihood estimators, we can assume that estimators are normally distributed around the population parameters.

$$\hat{oldsymbol{ heta}} \sim \mathcal{N}\left(oldsymbol{ heta}, \mathbb{V}\left(\hat{oldsymbol{ heta}}
ight)
ight)$$

Using this distributional assumption, a sampling distribution of  $\hat{\theta}$  which we refer to as  $\hat{\theta}^*$  can be generated by replacing the population parameters with sample estimates, that is,

$$\hat{oldsymbol{ heta}}^* \sim \mathcal{N}\left(\hat{oldsymbol{ heta}}, \hat{\mathbb{V}}\left(\hat{oldsymbol{ heta}}
ight)
ight).$$

#### Value

Returns an object of class ctmedmc which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("MCPhiSigma").

output A list simulated drift matrices.

# Author(s)

Ivan Jacob Agaloos Pesigan

#### See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

92 MCTotalCentral

## **Examples**

```
set.seed(42)
phi <- matrix(</pre>
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
sigma <- matrix(</pre>
  data = c(
    0.24455556, 0.02201587, -0.05004762,
    0.02201587, 0.07067800, 0.01539456,
    -0.05004762, 0.01539456, 0.07553061
  ),
  nrow = 3
)
MCPhiSigma(
  phi = phi,
  sigma = sigma,
  vcov_{theta} = 0.1 * diag(15),
  R = 100L # use a large value for R in actual research
)
```

MCTotalCentral

Monte Carlo Sampling Distribution of Total Effect Centrality Over a Specific Time Interval or a Range of Time Intervals

# **Description**

This function generates a Monte Carlo method sampling distribution of the total effect centrality at a particular time interval  $\Delta t$  using the first-order stochastic differential equation model drift matrix  $\Phi$ .

### Usage

```
MCTotalCentral(
  phi,
  vcov_phi_vec,
  delta_t,
  R,
  test_phi = TRUE,
  ncores = NULL,
  seed = NULL,
  tol = 0.01
)
```

MCTotalCentral 93

#### **Arguments**

phi Numeric matrix. The drift matrix ( $\Phi$ ), phi should have row and column names

pertaining to the variables in the system.

vcov\_phi\_vec Numeric matrix. The sampling variance-covariance matrix of vec  $(\Phi)$ .

delta\_t Numeric. Time interval ( $\Delta t$ ).

R Positive integer. Number of replications.

test\_phi Logical. If test\_phi = TRUE, the function tests the stability of the generated

drift matrix  $\Phi$ . If the test returns FALSE, the function generates a new drift

matrix  $\Phi$  and runs the test recursively until the test returns TRUE.

ncores Positive integer. Number of cores to use. If ncores = NULL, use a single core.

Consider using multiple cores when number of replications R is a large value.

seed Random seed.

tol Numeric. Smallest possible time interval to allow.

### **Details**

See TotalCentral() for more details.

#### **Monte Carlo Method:**

Let  $\theta$  be  $\operatorname{vec}(\Phi)$ , that is, the elements of the  $\Phi$  matrix in vector form sorted column-wise. Let  $\hat{\theta}$  be  $\operatorname{vec}(\hat{\Phi})$ . Based on the asymptotic properties of maximum likelihood estimators, we can assume that estimators are normally distributed around the population parameters.

$$\hat{oldsymbol{ heta}} \sim \mathcal{N}\left(oldsymbol{ heta}, \mathbb{V}\left(\hat{oldsymbol{ heta}}
ight)
ight)$$

Using this distributional assumption, a sampling distribution of  $\hat{\theta}$  which we refer to as  $\hat{\theta}^*$  can be generated by replacing the population parameters with sample estimates, that is,

$$\hat{oldsymbol{ heta}}^* \sim \mathcal{N}\left(\hat{oldsymbol{ heta}}, \hat{\mathbb{V}}\left(\hat{oldsymbol{ heta}}
ight)
ight).$$

Let  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$  be a parameter that is a function of the estimated parameters. A sampling distribution of  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}\right)$ , which we refer to as  $\mathbf{g}\left(\hat{\boldsymbol{\theta}}^*\right)$ , can be generated by using the simulated estimates to calculate  $\mathbf{g}$ . The standard deviations of the simulated estimates are the standard errors. Percentiles corresponding to  $100\left(1-\alpha\right)\%$  are the confidence intervals.

#### Value

Returns an object of class ctmedmc which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("MCTotalCentral").

output A list the length of which is equal to the length of delta\_t.

Each element in the output list has the following elements:

est A vector of total effect centrality.

thetahatstar A matrix of Monte Carlo total effect centrality.

94 MCTotalCentral

#### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), McPhiSigma(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

```
set.seed(42)
phi <- matrix(</pre>
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
vcov_phi_vec <- matrix(</pre>
  data = c(
    0.00843, 0.00040, -0.00151,
    -0.00600, -0.00033, 0.00110,
    0.00324, 0.00020, -0.00061,
    0.00040, 0.00374, 0.00016,
    -0.00022, -0.00273, -0.00016,
    0.00009, 0.00150, 0.00012,
    -0.00151, 0.00016, 0.00389,
    0.00103, -0.00007, -0.00283,
    -0.00050, 0.00000, 0.00156,
    -0.00600, -0.00022, 0.00103,
    0.00644, 0.00031, -0.00119,
    -0.00374, -0.00021, 0.00070,
    -0.00033, -0.00273, -0.00007,
    0.00031, 0.00287, 0.00013,
```

Med 95

```
-0.00014, -0.00170, -0.00012,
   0.00110, -0.00016, -0.00283,
   -0.00119, 0.00013, 0.00297,
   0.00063, -0.00004, -0.00177,
   0.00324, 0.00009, -0.00050,
   -0.00374, -0.00014, 0.00063,
   0.00495, 0.00024, -0.00093,
   0.00020, 0.00150, 0.00000,
   -0.00021, -0.00170, -0.00004,
   0.00024, 0.00214, 0.00012,
   -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
   -0.00093, 0.00012, 0.00223
 ),
 nrow = 9
)
# Specific time interval ------
MCTotalCentral(
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1,
 R = 100L # use a large value for R in actual research
)
# Range of time intervals ------
mc <- MCTotalCentral(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1:5,
 R = 100L # use a large value for R in actual research
)
plot(mc)
# Methods ------
# MCTotalCentral has a number of methods including
# print, summary, confint, and plot
print(mc)
summary(mc)
confint(mc, level = 0.95)
plot(mc)
```

Med

Total, Direct, and Indirect Effects of X on Y Through M Over a Specific Time Interval or a Range of Time Intervals

### **Description**

This function computes the total, direct, and indirect effects of the independent variable X on the dependent variable Y through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  or a range of

96 Med

time intervals using the first-order stochastic differential equation model's drift matrix  $\Phi$ .

### Usage

```
Med(phi, delta_t, from, to, med, tol = 0.01)
```

# **Arguments**

phi	Numeric matrix. The drift matrix $(\Phi)$ . phi should have row and column names pertaining to the variables in the system.
delta_t	Vector of positive numbers. Time interval ( $\Delta t$ ).
from	Character string. Name of the independent variable $X$ in phi.
to	Character string. Name of the dependent variable $Y$ in phi.
med	Character vector. Name/s of the mediator variable/s in phi.
tol	Numeric. Smallest possible time interval to allow.

#### **Details**

See Total(), Direct(), and Indirect() for more details.

# **Linear Stochastic Differential Equation Model:**

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{\nu} + \boldsymbol{\Lambda} \boldsymbol{\eta}_{i,t} + \boldsymbol{arepsilon}_{i,t}, \quad ext{with} \quad \boldsymbol{arepsilon}_{i,t} \sim \mathcal{N}\left(\mathbf{0}, oldsymbol{\Theta}
ight)$$

where  $\mathbf{y}_{i,t}$ ,  $\eta_{i,t}$ , and  $\varepsilon_{i,t}$  are random variables and  $\nu$ ,  $\Lambda$ , and  $\Theta$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\eta_{i,t}$  a vector of latent random variables, and  $\varepsilon_{i,t}$  a vector of random measurement errors, at time t and individual t.  $\nu$  denotes a vector of intercepts,  $\Lambda$  a matrix of factor loadings, and  $\Theta$  the covariance matrix of  $\varepsilon$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}} \mathbf{z}_{i,t}, \quad \text{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}\left(\mathbf{0}, \mathbf{I}\right)$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $\left(\Theta^{\frac{1}{2}}\right)\left(\Theta^{\frac{1}{2}}\right)' = \Theta$ . The dynamic structure is given by

$$\mathrm{d}oldsymbol{\eta}_{i,t} = \left(oldsymbol{\iota} + oldsymbol{\Phi}oldsymbol{\eta}_{i,t}
ight)\mathrm{d}t + oldsymbol{\Sigma}^{rac{1}{2}}\mathrm{d}\mathbf{W}_{i,t}$$

where  $\iota$  is a term which is unobserved and constant over time,  $\Phi$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\Sigma$  is the matrix of volatility or randomness in the process, and  $\mathrm{d} W$  is a Wiener process or Brownian motion, which represents random fluctuations.

#### Value

Returns an object of class ctmedmed which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("Med").

output A matrix of total, direct, and indirect effects.

Med 97

#### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
phi <- matrix(</pre>
 data = c(
   -0.357, 0.771, -0.450,
   0.0, -0.511, 0.729,
   0, 0, -0.693
 ),
 nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
# Specific time interval -------
Med(
 phi = phi,
 delta_t = 1,
 from = x^{*},
 to = "y",
 med = "m"
# Range of time intervals -------
med <- Med(
 phi = phi,
 delta_t = 1:30,
 from = "x",
 to = "y",
```

98 MedStd

MedStd

Standardized Total, Direct, and Indirect Effects of X on Y Through M Over a Specific Time Interval or a Range of Time Intervals

# Description

This function computes the standardized total, direct, and indirect effects of the independent variable X on the dependent variable Y through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model's drift matrix  $\mathbf{\Phi}$  and process noise covariance matrix  $\mathbf{\Sigma}$ .

# Usage

```
MedStd(phi, sigma, delta_t, from, to, med, tol = 0.01)
```

# Arguments

phi	Numeric matrix. The drift matrix $(\Phi)$ , phi should have row and column names pertaining to the variables in the system.
sigma	Numeric matrix. The process noise covariance matrix $(\Sigma)$ .
delta_t	Numeric. Time interval ( $\Delta t$ ).
from	Character string. Name of the independent variable $X$ in phi.
to	Character string. Name of the dependent variable $Y$ in phi.
med	Character vector. Name/s of the mediator variable/s in phi.
tol	Numeric. Smallest possible time interval to allow.

# **Details**

See TotalStd(), DirectStd(), and IndirectStd() for more details.

MedStd 99

#### Value

Returns an object of class ctmedmed which is a list with the following elements:

```
call Function call.

args Function arguments.

fun Function used ("MedStd").
```

**output** A standardized matrix of total, direct, and indirect effects.

### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
sigma <- matrix(
  data = c(
    0.24455556, 0.02201587, -0.05004762,
    0.02201587, 0.07067800, 0.01539456,
    -0.05004762, 0.01539456, 0.07553061
),</pre>
```

100 plot.ctmedboot

```
nrow = 3
)
# Specific time interval ------
MedStd(
 phi = phi,
 sigma = sigma,
 delta_t = 1,
 from = "x",
 to = "y",
 med = "m"
# Range of time intervals ------
med <- MedStd(</pre>
 phi = phi,
 sigma = sigma,
 delta_t = 1:30,
 from = "x",
 to = "y",
 med = "m"
)
plot(med)
# Methods -----
# MedStd has a number of methods including
# print, summary, and plot
med <- MedStd(</pre>
 phi = phi,
 sigma = sigma,
 delta_t = 1:5,
 from = "x",
 to = "y",
 med = "m"
)
print(med)
summary(med)
plot(med)
```

plot.ctmedboot

Plot Method for an Object of Class ctmedboot

## **Description**

Plot Method for an Object of Class ctmedboot

#### Usage

```
## S3 method for class 'ctmedboot'
plot(x, alpha = 0.05, col = NULL, type = "pc", ...)
```

plot.ctmedboot 101

# Arguments

X	Object of class ctmedboot.
alpha	Numeric. Significance level
col	Character vector. Optional argument. Character vector of colors.
type	Charater string. Confidence interval type, that is, type = "pc" for percentile; type = "bc" for bias corrected.
	Additional arguments.

### Value

Displays plots of point estimates and confidence intervals.

# Author(s)

Ivan Jacob Agaloos Pesigan

```
## Not run:
library(bootStateSpace)
# prepare parameters
## number of individuals
n <- 50
## time points
time <- 100
delta_t <- 0.10
## dynamic structure
p <- 3
mu0 < -rep(x = 0, times = p)
sigma0 <- matrix(</pre>
  data = c(
    1.0,
    0.2,
    0.2,
    0.2,
    1.0,
    0.2,
    0.2,
    0.2,
    1.0
  ),
  nrow = p
)
sigma0_1 \leftarrow t(chol(sigma0))
mu \leftarrow rep(x = 0, times = p)
phi <- matrix(</pre>
  data = c(
    -0.357,
    0.771,
    -0.450,
```

102 plot.ctmedboot

```
0.0,
    -0.511,
    0.729,
    0,
    0,
    -0.693
  ),
  nrow = p
)
sigma <- matrix(</pre>
  data = c(
    0.24455556,
    0.02201587,
    -0.05004762,
    0.02201587,
    0.07067800,
    0.01539456,
    -0.05004762,
    0.01539456,
    0.07553061
  ),
  nrow = p
)
sigma_l \leftarrow t(chol(sigma))
## measurement model
k <- 3
nu \leftarrow rep(x = 0, times = k)
lambda <- diag(k)</pre>
theta <- 0.2 * diag(k)
theta_l \leftarrow t(chol(theta))
boot <- PBSSMOUFixed(</pre>
  R = 1000L,
  path = getwd(),
  prefix = "ou",
  n = n,
  time = time,
  delta_t = delta_t,
  mu0 = mu0,
  sigma0_1 = sigma0_1,
  mu = mu,
  phi = phi,
  sigma_l = sigma_l,
  nu = nu,
  lambda = lambda,
  theta_l = theta_l,
  ncores = parallel::detectCores() - 1,
  seed = 42
)
phi_hat <- phi
colnames(phi_hat) \leftarrow rownames(phi_hat) \leftarrow c("x", "m", "y")
phi <- extract(object = boot, what = "phi")</pre>
```

plot.ctmeddelta 103

```
# Range of time intervals -----
boot <- BootMed(
    phi = phi,
    phi_hat = phi_hat,
    delta_t = 1:5,
    from = "x",
    to = "y",
    med = "m"
)
confint(boot)
confint(boot, type = "bc") # bias-corrected
## End(Not run)</pre>
```

plot.ctmeddelta

Plot Method for an Object of Class ctmeddelta

# **Description**

Plot Method for an Object of Class ctmeddelta

# Usage

```
## S3 method for class 'ctmeddelta'
plot(x, alpha = 0.05, col = NULL, ...)
```

# Arguments

X	Object of class ctmeddelta.
alpha	Numeric. Significance level
col	Character vector. Optional argument. Character vector of colors.
	Additional arguments.

### Value

Displays plots of point estimates and confidence intervals.

# Author(s)

Ivan Jacob Agaloos Pesigan

104 plot.ctmeddelta

```
phi <- matrix(</pre>
  data = c(
   -0.357, 0.771, -0.450,
   0.0, -0.511, 0.729,
   0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) \leftarrow rownames(phi) \leftarrow c("x", "m", "y")
vcov_phi_vec <- matrix(</pre>
  data = c(
    0.00843, 0.00040, -0.00151,
    -0.00600, -0.00033, 0.00110,
    0.00324, 0.00020, -0.00061,
    0.00040, 0.00374, 0.00016,
    -0.00022, -0.00273, -0.00016,
    0.00009, 0.00150, 0.00012,
    -0.00151, 0.00016, 0.00389,
    0.00103, -0.00007, -0.00283,
    -0.00050, 0.00000, 0.00156,
    -0.00600, -0.00022, 0.00103,
    0.00644, 0.00031, -0.00119,
    -0.00374, -0.00021, 0.00070,
    -0.00033, -0.00273, -0.00007,
    0.00031, 0.00287, 0.00013,
    -0.00014, -0.00170, -0.00012,
    0.00110, -0.00016, -0.00283,
    -0.00119, 0.00013, 0.00297,
    0.00063, -0.00004, -0.00177,
    0.00324, 0.00009, -0.00050,
    -0.00374, -0.00014, 0.00063,
    0.00495, 0.00024, -0.00093,
    0.00020, 0.00150, 0.00000,
    -0.00021, -0.00170, -0.00004,
    0.00024, 0.00214, 0.00012,
    -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
    -0.00093, 0.00012, 0.00223
  ),
  nrow = 9
)
# Range of time intervals ------
delta <- DeltaMed(</pre>
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  delta_t = 1:5,
  from = "x",
  to = "y",
  med = "m"
)
```

plot.ctmedmc 105

```
plot(delta)
```

plot.ctmedmc

Plot Method for an Object of Class ctmedmc

# Description

Plot Method for an Object of Class ctmedmc

# Usage

```
## S3 method for class 'ctmedmc'
plot(x, alpha = 0.05, col = NULL, ...)
```

### **Arguments**

```
    x Object of class ctmedmc.
    alpha Numeric. Significance level
    col Character vector. Optional argument. Character vector of colors.
    ... Additional arguments.
```

#### Value

Displays plots of point estimates and confidence intervals.

# Author(s)

Ivan Jacob Agaloos Pesigan

```
set.seed(42)
phi <- matrix(
    data = c(
        -0.357, 0.771, -0.450,
        0.0, -0.511, 0.729,
        0, 0, -0.693
    ),
    nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
    data = c(
        0.00843, 0.00040, -0.00151,
        -0.00600, -0.00033, 0.00110,
        0.00324, 0.00020, -0.00061,
        0.00040, 0.00374, 0.00016,</pre>
```

106 plot.ctmedmed

```
-0.00022, -0.00273, -0.00016,
   0.00009, 0.00150, 0.00012,
   -0.00151, 0.00016, 0.00389,
   0.00103, -0.00007, -0.00283,
   -0.00050, 0.00000, 0.00156,
   -0.00600, -0.00022, 0.00103,
   0.00644, 0.00031, -0.00119,
   -0.00374, -0.00021, 0.00070,
    -0.00033, -0.00273, -0.00007,
   0.00031, 0.00287, 0.00013,
    -0.00014, -0.00170, -0.00012,
   0.00110, -0.00016, -0.00283,
    -0.00119, 0.00013, 0.00297,
   0.00063, -0.00004, -0.00177,
   0.00324, 0.00009, -0.00050,
   -0.00374, -0.00014, 0.00063,
   0.00495, 0.00024, -0.00093,
   0.00020, 0.00150, 0.00000,
    -0.00021, -0.00170, -0.00004,
   0.00024, 0.00214, 0.00012,
    -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
    -0.00093, 0.00012, 0.00223
 ),
 nrow = 9
)
# Range of time intervals ------
mc <- MCMed(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1:5,
 from = "x",
 to = "y",
 med = "m",
 R = 100L # use a large value for R in actual research
plot(mc)
```

plot.ctmedmed

Plot Method for an Object of Class ctmedmed

## Description

Plot Method for an Object of Class ctmedmed

#### Usage

```
## S3 method for class 'ctmedmed'
plot(x, col = NULL, legend_pos = "topright", ...)
```

plot.ctmedtraj 107

# **Arguments**

Χ	Object of class ctmedmed.
col	Character vector. Optional argument. Character vector of colors.
legend_pos	Character vector. Optional argument. Legend position.
	Additional arguments.

### Value

Displays plots of point estimates and confidence intervals.

# Author(s)

Ivan Jacob Agaloos Pesigan

# **Examples**

```
phi <- matrix(</pre>
 data = c(
   -0.357, 0.771, -0.450,
   0.0, -0.511, 0.729,
   0, 0, -0.693
 ),
 nrow = 3
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
# Range of time intervals -----
med <- Med(
 phi = phi,
 delta_t = 1:5,
 from = "x",
 to = "y",
 med = "m"
)
plot(med)
```

plot.ctmedtraj

Plot Method for an Object of Class ctmedtraj

# **Description**

Plot Method for an Object of Class ctmedtraj

#### Usage

```
## S3 method for class 'ctmedtraj'
plot(x, legend_pos = "topright", total = TRUE, ...)
```

108 PosteriorBeta

# **Arguments**

Χ	Object of class ctmedtraj.
legend_pos	Character vector. Optional argument. Legend position.
total	Logical. If total = TRUE, include the total effect trajectory. If total = FALSE, exclude the total effect trajectory.
	Additional arguments.

### Value

Displays trajectory plots of the effects.

# Author(s)

Ivan Jacob Agaloos Pesigan

# **Examples**

```
phi <- matrix(</pre>
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
traj <- Trajectory(</pre>
  mu0 = c(3, 3, -3),
  time = 150,
  phi = phi,
  med = "m"
)
plot(traj)
```

PosteriorBeta

Posterior Sampling Distribution for the Elements of the Matrix of Lagged Coefficients Over a Specific Time Interval or a Range of Time Intervals

# **Description**

This function generates a posterior sampling distribution for the elements of the matrix of lagged coefficients  $\beta$  over a specific time interval  $\Delta t$  or a range of time intervals using the first-order stochastic differential equation model drift matrix  $\Phi$ .

PosteriorBeta 109

### Usage

```
PosteriorBeta(phi, delta_t, ncores = NULL, tol = 0.01)
```

### **Arguments**

phi Numeric matrix. The drift matrix ( $\Phi$ ), phi should have row and column names

pertaining to the variables in the system.

delta\_t Numeric. Time interval ( $\Delta t$ ).

ncores Positive integer. Number of cores to use. If ncores = NULL, use a single core.

Consider using multiple cores when number of replications R is a large value.

tol Numeric. Smallest possible time interval to allow.

#### **Details**

See Total().

#### Value

Returns an object of class ctmedmc which is a list with the following elements:

**call** Function call.

args Function arguments.

fun Function used ("PosteriorBeta").

**output** A list the length of which is equal to the length of delta\_t.

Each element in the output list has the following elements:

est A vector of total, direct, and indirect effects.

**thetahatstar** A matrix of Monte Carlo total, direct, and indirect effects.

### Author(s)

Ivan Jacob Agaloos Pesigan

# References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

110 PosteriorBeta

### See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), TotalCentral(), TotalStd(), Trajectory()
```

```
phi <- matrix(</pre>
 data = c(
   -0.357, 0.771, -0.450,
   0.0, -0.511, 0.729,
   0, 0, -0.693
 ),
 nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
vcov_phi_vec <- matrix(</pre>
 data = c(
   0.00843, 0.00040, -0.00151,
    -0.00600, -0.00033, 0.00110,
    0.00324, 0.00020, -0.00061,
    0.00040, 0.00374, 0.00016,
    -0.00022, -0.00273, -0.00016,
    0.00009, 0.00150, 0.00012,
    -0.00151, 0.00016, 0.00389,
    0.00103, -0.00007, -0.00283.
    -0.00050, 0.00000, 0.00156,
    -0.00600, -0.00022, 0.00103,
    0.00644, 0.00031, -0.00119,
    -0.00374, -0.00021, 0.00070,
    -0.00033, -0.00273, -0.00007,
    0.00031, 0.00287, 0.00013,
    -0.00014, -0.00170, -0.00012,
    0.00110, -0.00016, -0.00283,
    -0.00119, 0.00013, 0.00297,
    0.00063, -0.00004, -0.00177,
    0.00324, 0.00009, -0.00050,
    -0.00374, -0.00014, 0.00063,
    0.00495, 0.00024, -0.00093,
    0.00020, 0.00150, 0.00000,
    -0.00021, -0.00170, -0.00004,
    0.00024, 0.00214, 0.00012,
    -0.00061, 0.00012, 0.00156,
    0.00070, -0.00012, -0.00177,
    -0.00093, 0.00012, 0.00223
 ),
 nrow = 9
)
```

PosteriorIndirectCentral 111

```
phi <- MCPhi(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 R = 1000L
)$output
# Specific time interval ------
PosteriorBeta(
 phi = phi,
 delta_t = 1
# Range of time intervals ------
posterior <- PosteriorBeta(</pre>
 phi = phi,
 delta_t = 1:5
plot(posterior)
# Methods -----
# PosteriorBeta has a number of methods including
# print, summary, confint, and plot
print(posterior)
summary(posterior)
confint(posterior, level = 0.95)
plot(posterior)
```

PosteriorIndirectCentral

Posterior Distribution of the Indirect Effect Centrality Over a Specific Time Interval or a Range of Time Intervals

### **Description**

This function generates a posterior distribution of the indirect effect centrality over a specific time interval  $\Delta t$  or a range of time intervals using the posterior distribution of the first-order stochastic differential equation model drift matrix  $\Phi$ .

### Usage

```
PosteriorIndirectCentral(phi, delta_t, ncores = NULL, tol = 0.01)
```

### **Arguments**

phi	List of numeric matrices. Each element of the list is a sample from the posterior
	distribution of the drift matrix ( $\Phi$ ). Each matrix should have row and column
	names pertaining to the variables in the system.

delta\_t Numeric. Time interval  $(\Delta t)$ .

112 PosteriorIndirectCentral

ncores Positive integer. Number of cores to use. If ncores = NULL, use a single core.

Consider using multiple cores when number of replications R is a large value.

tol Numeric. Smallest possible time interval to allow.

#### **Details**

See TotalCentral() for more details.

#### Value

Returns an object of class ctmedmc which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("PosteriorIndirectCentral").

**output** A list the length of which is equal to the length of delta\_t.

Each element in the output list has the following elements:

est Mean of the posterior distribution of the total, direct, and indirect effects.

thetahatstar Posterior distribution of the total, direct, and indirect effects.

### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), MCBetaStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()

PosteriorIndirectCentral 113

```
phi <- matrix(</pre>
  data = c(
   -0.357, 0.771, -0.450,
   0.0, -0.511, 0.729,
   0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) \leftarrow rownames(phi) \leftarrow c("x", "m", "y")
vcov_phi_vec <- matrix(</pre>
  data = c(
    0.00843, 0.00040, -0.00151,
    -0.00600, -0.00033, 0.00110,
    0.00324, 0.00020, -0.00061,
    0.00040, 0.00374, 0.00016,
    -0.00022, -0.00273, -0.00016,
    0.00009, 0.00150, 0.00012,
    -0.00151, 0.00016, 0.00389,
    0.00103, -0.00007, -0.00283,
    -0.00050, 0.00000, 0.00156,
    -0.00600, -0.00022, 0.00103,
   0.00644, 0.00031, -0.00119,
   -0.00374, -0.00021, 0.00070,
    -0.00033, -0.00273, -0.00007,
   0.00031, 0.00287, 0.00013,
    -0.00014, -0.00170, -0.00012,
   0.00110, -0.00016, -0.00283,
    -0.00119, 0.00013, 0.00297,
    0.00063, -0.00004, -0.00177,
    0.00324, 0.00009, -0.00050,
    -0.00374, -0.00014, 0.00063,
    0.00495, 0.00024, -0.00093,
    0.00020, 0.00150, 0.00000,
    -0.00021, -0.00170, -0.00004,
   0.00024, 0.00214, 0.00012,
    -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
   -0.00093, 0.00012, 0.00223
  ),
  nrow = 9
)
phi <- MCPhi(</pre>
  phi = phi,
  vcov_phi_vec = vcov_phi_vec,
  R = 1000L
)$output
# Specific time interval ------
PosteriorIndirectCentral(
  phi = phi,
```

114 PosteriorMed

PosteriorMed

Posterior Distribution of Total, Direct, and Indirect Effects of X on Y Through M Over a Specific Time Interval or a Range of Time Intervals

### **Description**

This function generates a posterior distribution of the total, direct and indirect effects of the independent variable X on the dependent variable Y through mediator variables  $\mathbf{m}$  over a specific time interval  $\Delta t$  or a range of time intervals using the posterior distribution of the first-order stochastic differential equation model drift matrix  $\mathbf{\Phi}$ .

### Usage

```
PosteriorMed(phi, delta_t, from, to, med, ncores = NULL, tol = 0.01)
```

### **Arguments**

phi	List of numeric matrices. Each element of the list is a sample from the posterior distribution of the drift matrix ( $\Phi$ ). Each matrix should have row and column names pertaining to the variables in the system.
delta_t	Numeric. Time interval ( $\Delta t$ ).
from	Character string. Name of the independent variable $X$ in phi.
to	Character string. Name of the dependent variable $Y$ in phi.
med	Character vector. Name/s of the mediator variable/s in phi.
ncores	Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.
tol	Numeric. Smallest possible time interval to allow.

PosteriorMed 115

#### **Details**

See Total(), Direct(), and Indirect() for more details.

#### Value

Returns an object of class ctmedmc which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("PosteriorMed").

output A list the length of which is equal to the length of delta\_t.

Each element in the output list has the following elements:

est Mean of the posterior distribution of the total, direct, and indirect effects.

thetahatstar Posterior distribution of the total, direct, and indirect effects.

#### Author(s)

Ivan Jacob Agaloos Pesigan

### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

### See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
),</pre>
```

116 PosteriorMed

```
nrow = 3
)
colnames(phi) \leftarrow rownames(phi) \leftarrow c("x", "m", "y")
vcov_phi_vec <- matrix(</pre>
 data = c(
   0.00843, 0.00040, -0.00151,
   -0.00600, -0.00033, 0.00110,
   0.00324, 0.00020, -0.00061,
   0.00040, 0.00374, 0.00016,
   -0.00022, -0.00273, -0.00016,
   0.00009, 0.00150, 0.00012,
   -0.00151, 0.00016, 0.00389,
   0.00103, -0.00007, -0.00283,
   -0.00050, 0.00000, 0.00156,
   -0.00600, -0.00022, 0.00103,
   0.00644, 0.00031, -0.00119,
   -0.00374, -0.00021, 0.00070,
   -0.00033, -0.00273, -0.00007,
   0.00031, 0.00287, 0.00013,
   -0.00014, -0.00170, -0.00012,
   0.00110, -0.00016, -0.00283,
    -0.00119, 0.00013, 0.00297,
   0.00063, -0.00004, -0.00177,
   0.00324, 0.00009, -0.00050,
   -0.00374, -0.00014, 0.00063,
   0.00495, 0.00024, -0.00093,
   0.00020, 0.00150, 0.00000,
    -0.00021, -0.00170, -0.00004,
   0.00024, 0.00214, 0.00012,
   -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
   -0.00093, 0.00012, 0.00223
 ),
 nrow = 9
)
phi <- MCPhi(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 R = 1000L
)$output
# Specific time interval ------
PosteriorMed(
 phi = phi,
 delta_t = 1,
 from = "x",
 to = "y",
 med = "m"
)
# Range of time intervals ------
posterior <- PosteriorMed(</pre>
```

PosteriorTotalCentral 117

PosteriorTotalCentral Posterior Distribution of the Total Effect Centrality Over a Specific Time Interval or a Range of Time Intervals

# Description

This function generates a posterior distribution of the total effect centrality over a specific time interval  $\Delta t$  or a range of time intervals using the posterior distribution of the first-order stochastic differential equation model drift matrix  $\Phi$ .

### Usage

```
PosteriorTotalCentral(phi, delta_t, ncores = NULL, tol = 0.01)
```

### **Arguments**

phi	List of numeric matrices. Each element of the list is a sample from the posterior distribution of the drift matrix ( $\Phi$ ). Each matrix should have row and column names pertaining to the variables in the system.
delta_t	Numeric. Time interval ( $\Delta t$ ).
ncores	Positive integer. Number of cores to use. If ncores = NULL, use a single core. Consider using multiple cores when number of replications R is a large value.
tol	Numeric. Smallest possible time interval to allow.

### **Details**

See TotalCentral() for more details.

118 PosteriorTotalCentral

#### Value

Returns an object of class ctmedmc which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("PosteriorTotalCentral").

**output** A list the length of which is equal to the length of delta\_t.

Each element in the output list has the following elements:

est Mean of the posterior distribution of the total, direct, and indirect effects.

thetahatstar Posterior distribution of the total, direct, and indirect effects.

#### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(</pre>
```

PosteriorTotalCentral 119

```
0.00843, 0.00040, -0.00151,
   -0.00600, -0.00033, 0.00110,
   0.00324, 0.00020, -0.00061,
   0.00040, 0.00374, 0.00016,
   -0.00022, -0.00273, -0.00016,
   0.00009, 0.00150, 0.00012,
   -0.00151, 0.00016, 0.00389,
   0.00103, -0.00007, -0.00283,
   -0.00050, 0.00000, 0.00156,
   -0.00600, -0.00022, 0.00103,
   0.00644, 0.00031, -0.00119,
   -0.00374, -0.00021, 0.00070,
   -0.00033, -0.00273, -0.00007,
   0.00031, 0.00287, 0.00013,
   -0.00014, -0.00170, -0.00012,
   0.00110, -0.00016, -0.00283,
   -0.00119, 0.00013, 0.00297,
   0.00063, -0.00004, -0.00177,
   0.00324, 0.00009, -0.00050,
   -0.00374, -0.00014, 0.00063,
   0.00495, 0.00024, -0.00093,
   0.00020, 0.00150, 0.00000,
   -0.00021, -0.00170, -0.00004,
   0.00024, 0.00214, 0.00012,
   -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
   -0.00093, 0.00012, 0.00223
 ),
 nrow = 9
)
phi <- MCPhi(
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 R = 1000L
)$output
# Specific time interval ------
PosteriorTotalCentral(
 phi = phi,
 delta_t = 1
)
# Range of time intervals ------
posterior <- PosteriorTotalCentral(</pre>
 phi = phi,
 delta_t = 1:5
# Methods ------
# PosteriorTotalCentral has a number of methods including
# print, summary, confint, and plot
print(posterior)
```

print.ctmedboot

```
summary(posterior)
confint(posterior, level = 0.95)
plot(posterior)
```

print.ctmedboot

Print Method for Object of Class ctmedboot

# Description

Print Method for Object of Class ctmedboot

### Usage

```
## S3 method for class 'ctmedboot'
print(x, alpha = 0.05, digits = 4, type = "pc", ...)
```

### **Arguments**

x an object of class ctmedboot. alpha Numeric vector. Significance level  $\alpha$ . digits Integer indicating the number of decimal places to display. type Charater string. Confidence interval type, that is, type = "pc" for percentile; type = "bc" for bias corrected. ... further arguments.

#### Value

Prints a list of matrices of time intervals, estimates, standard errors, number of bootstrap replications, and confidence intervals.

#### Author(s)

Ivan Jacob Agaloos Pesigan

```
## Not run:
library(bootStateSpace)
# prepare parameters
## number of individuals
n <- 50
## time points
time <- 100
delta_t <- 0.10
## dynamic structure
p <- 3
mu0 <- rep(x = 0, times = p)</pre>
```

print.ctmedboot 121

```
sigma0 <- matrix(</pre>
  data = c(
    1.0,
    0.2,
    0.2,
    0.2,
    1.0,
    0.2,
    0.2,
    0.2,
    1.0
  ),
  nrow = p
)
sigma0_l \leftarrow t(chol(sigma0))
mu \leftarrow rep(x = 0, times = p)
phi <- matrix(</pre>
  data = c(
    -0.357,
    0.771,
    -0.450,
    0.0,
    -0.511,
    0.729,
    0,
    0,
    -0.693
  ),
  nrow = p
sigma <- matrix(</pre>
  data = c(
    0.24455556,
    0.02201587,
    -0.05004762,
    0.02201587,
    0.07067800,
    0.01539456,
    -0.05004762,
    0.01539456,
    0.07553061
  ),
  nrow = p
)
sigma_l <- t(chol(sigma))</pre>
## measurement model
k <- 3
nu \leftarrow rep(x = 0, times = k)
lambda <- diag(k)</pre>
theta <- 0.2 * diag(k)
theta_l \leftarrow t(chol(theta))
boot <- PBSSMOUFixed(</pre>
```

122 print.ctmeddelta

```
R = 1000L
 path = getwd(),
 prefix = "ou",
 n = n,
 time = time,
 delta_t = delta_t,
 mu0 = mu0,
 sigma0_1 = sigma0_1,
 mu = mu,
 phi = phi,
 sigma_l = sigma_l,
 nu = nu,
 lambda = lambda,
 theta_l = theta_l,
 ncores = parallel::detectCores() - 1,
 seed = 42
)
phi_hat <- phi</pre>
colnames(phi_hat) <- rownames(phi_hat) <- c("x", "m", "y")</pre>
phi <- extract(object = boot, what = "phi")</pre>
# Specific time interval ------
boot <- BootMed(</pre>
 phi = phi,
 phi_hat = phi_hat,
 delta_t = 1,
 from = "x",
 to = "y",
 med = "m"
)
print(boot)
print(boot, type = "bc") # bias-corrected
# Range of time intervals ------
boot <- BootMed(</pre>
 phi = phi,
 phi_hat = phi_hat,
 delta_t = 1:5,
 from = "x",
 to = "y",
 med = "m"
)
print(boot)
print(boot, type = "bc") # bias-corrected
## End(Not run)
```

print.ctmeddelta 123

### **Description**

Print Method for Object of Class ctmeddelta

### Usage

```
## S3 method for class 'ctmeddelta'
print(x, alpha = 0.05, digits = 4, ...)
```

### **Arguments**

```
x an object of class ctmeddelta.  
alpha Numeric vector. Significance level \alpha.  
digits Integer indicating the number of decimal places to display.  
... further arguments.
```

### Value

Prints a list of matrices of time intervals, estimates, standard errors, test statistics, p-values, and confidence intervals.

#### Author(s)

Ivan Jacob Agaloos Pesigan

```
phi <- matrix(</pre>
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
vcov_phi_vec <- matrix(</pre>
  data = c(
    0.00843, 0.00040, -0.00151,
    -0.00600, -0.00033, 0.00110,
    0.00324, 0.00020, -0.00061,
    0.00040, 0.00374, 0.00016,
    -0.00022, -0.00273, -0.00016,
    0.00009, 0.00150, 0.00012,
    -0.00151, 0.00016, 0.00389,
    0.00103, -0.00007, -0.00283,
    -0.00050, 0.00000, 0.00156,
    -0.00600, -0.00022, 0.00103,
    0.00644, 0.00031, -0.00119,
    -0.00374, -0.00021, 0.00070,
    -0.00033, -0.00273, -0.00007,
```

124 print.ctmedeffect

```
0.00031, 0.00287, 0.00013,
   -0.00014, -0.00170, -0.00012,
   0.00110, -0.00016, -0.00283,
   -0.00119, 0.00013, 0.00297,
   0.00063, -0.00004, -0.00177,
   0.00324, 0.00009, -0.00050,
   -0.00374, -0.00014, 0.00063,
   0.00495, 0.00024, -0.00093,
   0.00020, 0.00150, 0.00000,
   -0.00021, -0.00170, -0.00004,
   0.00024, 0.00214, 0.00012,
   -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
   -0.00093, 0.00012, 0.00223
 ),
 nrow = 9
)
# Specific time interval ------
delta <- DeltaMed(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1,
 from = "x",
 to = "y",
 med = "m"
print(delta)
# Range of time intervals ------
delta <- DeltaMed(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1:5,
 from = x^{*},
 to = "y",
 med = "m"
print(delta)
```

print.ctmedeffect

Print Method for Object of Class ctmedeffect

### **Description**

Print Method for Object of Class ctmedeffect

print.ctmedeffect 125

### Usage

```
## S3 method for class 'ctmedeffect'
print(x, digits = 4, ...)
```

### **Arguments**

x an object of class ctmedeffect.digits Integer indicating the number of decimal places to display.... further arguments.

#### Value

Prints the effects.

### Author(s)

Ivan Jacob Agaloos Pesigan

```
phi <- matrix(</pre>
 data = c(
  -0.357, 0.771, -0.450,
  0.0, -0.511, 0.729,
  0, 0, -0.693
 ),
 nrow = 3
colnames(phi) \leftarrow rownames(phi) \leftarrow c("x", "m", "y")
delta_t <- 1
# Time Interval of One ------
## Total Effect -----
total_dt <- Total(</pre>
 phi = phi,
 delta_t = delta_t
)
print(total_dt)
direct_dt <- Direct(</pre>
 phi = phi,
 delta_t = delta_t,
 from = "x",
 to = "y",
 med = "m"
print(direct_dt)
## Indirect Effect ------
```

print.ctmedmc

```
indirect_dt <- Indirect(
  phi = phi,
  delta_t = delta_t,
  from = "x",
  to = "y",
  med = "m"
)
print(indirect_dt)</pre>
```

print.ctmedmc

Print Method for Object of Class ctmedmc

### **Description**

Print Method for Object of Class ctmedmc

### Usage

```
## S3 method for class 'ctmedmc'
print(x, alpha = 0.05, digits = 4, ...)
```

# Arguments

x an object of class ctmedmc. alpha Numeric vector. Significance level  $\alpha$ . digits Integer indicating the number of decimal places to display.

... further arguments.

# Value

Prints a list of matrices of time intervals, estimates, standard errors, number of Monte Carlo replications, and confidence intervals.

# Author(s)

Ivan Jacob Agaloos Pesigan

```
set.seed(42)
phi <- matrix(
    data = c(
        -0.357, 0.771, -0.450,
        0.0, -0.511, 0.729,
        0, 0, -0.693
    ),
    nrow = 3</pre>
```

print.ctmedmc 127

```
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
vcov_phi_vec <- matrix(</pre>
 data = c(
   0.00843, 0.00040, -0.00151,
   -0.00600, -0.00033, 0.00110,
   0.00324, 0.00020, -0.00061,
   0.00040, 0.00374, 0.00016,
   -0.00022, -0.00273, -0.00016,
   0.00009, 0.00150, 0.00012,
   -0.00151, 0.00016, 0.00389,
   0.00103, -0.00007, -0.00283,
   -0.00050, 0.00000, 0.00156,
   -0.00600, -0.00022, 0.00103,
   0.00644, 0.00031, -0.00119,
   -0.00374, -0.00021, 0.00070,
   -0.00033, -0.00273, -0.00007,
   0.00031, 0.00287, 0.00013,
   -0.00014, -0.00170, -0.00012,
   0.00110, -0.00016, -0.00283,
   -0.00119, 0.00013, 0.00297,
   0.00063, -0.00004, -0.00177,
   0.00324, 0.00009, -0.00050,
   -0.00374, -0.00014, 0.00063,
   0.00495, 0.00024, -0.00093,
   0.00020, 0.00150, 0.00000,
   -0.00021, -0.00170, -0.00004,
   0.00024, 0.00214, 0.00012,
   -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
   -0.00093, 0.00012, 0.00223
 ),
 nrow = 9
)
# Specific time interval ------
mc <- MCMed(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1,
 from = "x",
 to = "y",
 med = "m"
 R = 100L # use a large value for R in actual research
)
print(mc)
# Range of time intervals ------
mc <- MCMed(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1:5,
 from = "x",
```

128 print.ctmedmcphi

```
to = "y",
  med = "m",
  R = 100L # use a large value for R in actual research
)
print(mc)
```

print.ctmedmcphi

Print Method for Object of Class ctmedmcphi

# Description

Print Method for Object of Class ctmedmcphi

# Usage

```
## S3 method for class 'ctmedmcphi'
print(x, digits = 4, ...)
```

### **Arguments**

```
x an object of class ctmedmcphi.digits Integer indicating the number of decimal places to display.... further arguments.
```

### Value

Prints a list of drift matrices.

### Author(s)

Ivan Jacob Agaloos Pesigan

```
set.seed(42)
phi <- matrix(
   data = c(
        -0.357, 0.771, -0.450,
        0.0, -0.511, 0.729,
        0, 0, -0.693
   ),
   nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
mc <- MCPhi(
   phi = phi,
   vcov_phi_vec = 0.1 * diag(9),
   R = 100L # use a large value for R in actual research</pre>
```

print.ctmedmed 129

```
print(mc)
```

print.ctmedmed

Print Method for Object of Class ctmedmed

# Description

Print Method for Object of Class ctmedmed

### Usage

```
## S3 method for class 'ctmedmed'
print(x, digits = 4, ...)
```

### **Arguments**

```
x an object of class ctmedmed.digits Integer indicating the number of decimal places to display.... further arguments.
```

#### Value

Prints a matrix of effects.

### Author(s)

Ivan Jacob Agaloos Pesigan

```
phi <- matrix(</pre>
 data = c(
   -0.357, 0.771, -0.450,
   0.0, -0.511, 0.729,
   0, 0, -0.693
 ),
 nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
# Specific time interval ------
med <- Med(
 phi = phi,
 delta_t = 1,
 from = "x",
 to = "y",
 med = "m"
```

print.ctmedtraj

```
print(med)

# Range of time intervals -----
med <- Med(
   phi = phi,
    delta_t = 1:5,
   from = "x",
   to = "y",
   med = "m"
)
print(med)</pre>
```

print.ctmedtraj

Print Method for Object of Class ctmedtraj

### **Description**

Print Method for Object of Class ctmedtraj

### Usage

```
## S3 method for class 'ctmedtraj'
print(x, ...)
```

### **Arguments**

x an object of class ctmedtraj.... further arguments.

### Value

Prints a data frame of simulated data.

# Author(s)

Ivan Jacob Agaloos Pesigan

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)</pre>
```

summary.ctmedboot 131

```
colnames(phi) <- rownames(phi) <- c("x", "m", "y")

traj <- Trajectory(
  mu0 = c(3, 3, -3),
  time = 150,
  phi = phi,
  med = "m"
)

print(traj)</pre>
```

summary.ctmedboot

Summary Method for an Object of Class ctmedboot

# Description

Summary Method for an Object of Class ctmedboot

# Usage

```
## S3 method for class 'ctmedboot'
summary(object, alpha = 0.05, type = "pc", ...)
```

# Arguments

object	Object of class ctmedboot.
alpha	Numeric vector. Significance level $\alpha$ .
type	Charater string. Confidence interval type, that is, type = "pc" for percentile; type = "bc" for bias corrected.
	additional arguments.

# Value

Returns a data frame of effects, time intervals, estimates, standard errors, number of bootstrap replications, and confidence intervals.

# Author(s)

Ivan Jacob Agaloos Pesigan

132 summary.ctmedboot

```
## Not run:
library(bootStateSpace)
# prepare parameters
## number of individuals
n <- 50
## time points
time <- 100
delta_t <- 0.10
## dynamic structure
p <- 3
mu0 < -rep(x = 0, times = p)
sigma0 <- matrix(</pre>
  data = c(
    1.0,
    0.2,
    0.2,
    0.2,
    1.0,
    0.2,
    0.2,
    0.2,
    1.0
  ),
  nrow = p
)
sigma0_l <- t(chol(sigma0))</pre>
mu \leftarrow rep(x = 0, times = p)
phi <- matrix(</pre>
  data = c(
    -0.357,
    0.771,
    -0.450,
    0.0,
    -0.511,
    0.729,
   0,
    0,
    -0.693
 ),
 nrow = p
)
sigma <- matrix(</pre>
 data = c(
    0.24455556,
    0.02201587,
    -0.05004762,
    0.02201587,
    0.07067800,
    0.01539456,
    -0.05004762,
    0.01539456,
```

summary.ctmedboot 133

```
0.07553061
 ),
 nrow = p
)
sigma_l <- t(chol(sigma))</pre>
## measurement model
k <- 3
nu \leftarrow rep(x = 0, times = k)
lambda <- diag(k)</pre>
theta <- 0.2 * diag(k)
theta_l <- t(chol(theta))</pre>
boot <- PBSSMOUFixed(</pre>
 R = 1000L
 path = getwd(),
 prefix = "ou",
 n = n,
 time = time,
 delta_t = delta_t,
 mu0 = mu0,
 sigma0_1 = sigma0_1,
 mu = mu,
 phi = phi,
 sigma_l = sigma_l,
 nu = nu,
 lambda = lambda,
 theta_l = theta_l,
 ncores = parallel::detectCores() - 1,
 seed = 42
)
phi_hat <- phi</pre>
colnames(phi_hat) <- rownames(phi_hat) <- c("x", "m", "y")</pre>
phi <- extract(object = boot, what = "phi")</pre>
# Specific time interval ------
boot <- BootMed(</pre>
 phi = phi,
 phi_hat = phi_hat,
 delta_t = 1,
 from = "x",
 to = "y",
 med = "m"
)
summary(boot)
summary(boot, type = "bc") # bias-corrected
# Range of time intervals -----
boot <- BootMed(</pre>
 phi = phi,
 phi_hat = phi_hat,
 delta_t = 1:5,
 from = "x",
 to = "y",
```

134 summary.ctmeddelta

```
med = "m"
)
summary(boot)
summary(boot, type = "bc") # bias-corrected
## End(Not run)
```

summary.ctmeddelta

Summary Method for an Object of Class ctmeddelta

# Description

Summary Method for an Object of Class ctmeddelta

### Usage

```
## S3 method for class 'ctmeddelta'
summary(object, alpha = 0.05, ...)
```

### **Arguments**

object Object of class ctmeddelta. alpha Numeric vector. Significance level  $\alpha$ . ... additional arguments.

### Value

Returns a data frame of effects, time intervals, estimates, standard errors, test statistics, p-values, and confidence intervals.

### Author(s)

Ivan Jacob Agaloos Pesigan

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")
vcov_phi_vec <- matrix(
  data = c(
    0.00843, 0.00040, -0.00151,</pre>
```

summary.ctmeddelta 135

```
-0.00600, -0.00033, 0.00110,
   0.00324, 0.00020, -0.00061,
   0.00040, 0.00374, 0.00016,
   -0.00022, -0.00273, -0.00016,
   0.00009, 0.00150, 0.00012,
   -0.00151, 0.00016, 0.00389,
   0.00103, -0.00007, -0.00283,
   -0.00050, 0.00000, 0.00156,
   -0.00600, -0.00022, 0.00103,
   0.00644, 0.00031, -0.00119,
   -0.00374, -0.00021, 0.00070,
   -0.00033, -0.00273, -0.00007,
   0.00031, 0.00287, 0.00013,
   -0.00014, -0.00170, -0.00012,
   0.00110, -0.00016, -0.00283,
   -0.00119, 0.00013, 0.00297,
   0.00063, -0.00004, -0.00177,
   0.00324, 0.00009, -0.00050,
   -0.00374, -0.00014, 0.00063,
   0.00495, 0.00024, -0.00093,
   0.00020, 0.00150, 0.00000,
   -0.00021, -0.00170, -0.00004,
   0.00024, 0.00214, 0.00012,
   -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
   -0.00093, 0.00012, 0.00223
 ),
 nrow = 9
)
# Specific time interval ------
delta <- DeltaMed(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1,
 from = "x",
 to = "y",
 med = "m"
summary(delta)
# Range of time intervals -----
delta <- DeltaMed(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1:5,
 from = "x",
 to = "y",
 med = "m"
)
summary(delta)
```

summary.ctmedmc

summary.ctmedmc

Summary Method for an Object of Class ctmedmc

### **Description**

Summary Method for an Object of Class ctmedmc

### Usage

```
## S3 method for class 'ctmedmc'
summary(object, alpha = 0.05, ...)
```

### **Arguments**

```
object Object of class ctmedmc.  
alpha Numeric vector. Significance level \alpha.  
additional arguments.
```

#### Value

Returns a data frame of effects, time intervals, estimates, standard errors, number of Monte Carlo replications, and confidence intervals.

### Author(s)

Ivan Jacob Agaloos Pesigan

```
set.seed(42)
phi <- matrix(</pre>
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
vcov_phi_vec <- matrix(</pre>
  data = c(
    0.00843, 0.00040, -0.00151,
    -0.00600, -0.00033, 0.00110,
    0.00324, 0.00020, -0.00061,
    0.00040, 0.00374, 0.00016,
    -0.00022, -0.00273, -0.00016,
    0.00009, 0.00150, 0.00012,
    -0.00151, 0.00016, 0.00389,
    0.00103, -0.00007, -0.00283,
```

summary.ctmedmed 137

```
-0.00050, 0.00000, 0.00156,
   -0.00600, -0.00022, 0.00103,
   0.00644, 0.00031, -0.00119,
   -0.00374, -0.00021, 0.00070,
   -0.00033, -0.00273, -0.00007,
   0.00031, 0.00287, 0.00013,
   -0.00014, -0.00170, -0.00012,
   0.00110, -0.00016, -0.00283,
   -0.00119, 0.00013, 0.00297,
   0.00063, -0.00004, -0.00177,
   0.00324, 0.00009, -0.00050,
   -0.00374, -0.00014, 0.00063,
   0.00495, 0.00024, -0.00093,
   0.00020, 0.00150, 0.00000,
   -0.00021, -0.00170, -0.00004,
   0.00024, 0.00214, 0.00012,
   -0.00061, 0.00012, 0.00156,
   0.00070, -0.00012, -0.00177,
   -0.00093, 0.00012, 0.00223
 ),
 nrow = 9
)
# Specific time interval ------
mc <- MCMed(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1,
 from = "x",
 to = "y",
 med = "m",
 R = 100L # use a large value for R in actual research
)
summary(mc)
# Range of time intervals ------
mc <- MCMed(</pre>
 phi = phi,
 vcov_phi_vec = vcov_phi_vec,
 delta_t = 1:5,
 from = "x",
 to = "y",
 med = "m"
 R = 100L # use a large value for R in actual research
)
summary(mc)
```

138 summary.ctmedmed

### **Description**

Summary Method for an Object of Class ctmedmed

### Usage

```
## S3 method for class 'ctmedmed'
summary(object, digits = 4, ...)
```

### **Arguments**

```
object an object of class ctmedmed.

digits Integer indicating the number of decimal places to display.

further arguments.
```

### Value

Returns a matrix of effects.

### Author(s)

Ivan Jacob Agaloos Pesigan

```
phi <- matrix(</pre>
 data = c(
   -0.357, 0.771, -0.450,
   0.0, -0.511, 0.729,
   0, 0, -0.693
 ),
 nrow = 3
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
# Specific time interval ------
med <- Med(
 phi = phi,
 delta_t = 1,
 from = x^{*},
 to = "y",
 med = "m"
)
summary(med)
# Range of time intervals -----
med <- Med(
 phi = phi,
 delta_t = 1:5,
 from = "x",
 to = "y",
 med = "m"
```

```
)
summary(med)
```

summary.ctmedposteriorphi

Summary Method for Object of Class ctmedposteriorphi

# Description

Summary Method for Object of Class ctmedposteriorphi

### Usage

```
## S3 method for class 'ctmedposteriorphi'
summary(object, ...)
```

### Arguments

```
object an object of class ctmedposteriorphi.
... further arguments.
```

### Value

Returns a list of the posterior means (in matrix form) and covariance matrix.

### Author(s)

Ivan Jacob Agaloos Pesigan

summary.ctmedtraj

Summary Method for an Object of Class ctmedtraj

# **Description**

Summary Method for an Object of Class ctmedtraj

#### **Usage**

```
## S3 method for class 'ctmedtraj'
summary(object, ...)
```

# Arguments

```
object an object of class ctmedtraj.
... further arguments.
```

Total

### Value

Returns a data frame of simulated data.

# Author(s)

Ivan Jacob Agaloos Pesigan

### **Examples**

```
phi <- matrix(
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
),
  nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")

traj <- Trajectory(
  mu0 = c(3, 3, -3),
    time = 150,
    phi = phi,
    med = "m"
)
summary(traj)</pre>
```

Total

Total Effect Matrix Over a Specific Time Interval

# **Description**

This function computes the total effects matrix over a specific time interval  $\Delta t$  using the first-order stochastic differential equation model's drift matrix  $\Phi$ .

### Usage

```
Total(phi, delta_t)
```

### **Arguments**

Phi Numeric matrix. The drift matrix  $(\Phi)$ , phi should have row and column names pertaining to the variables in the system.

delta\_t Numeric. Time interval ( $\Delta t$ ).

Total 141

#### **Details**

The total effect matrix over a specific time interval  $\Delta t$  is given by

$$Total_{\Delta t} = \exp(\Delta t \mathbf{\Phi})$$

where  $\Phi$  denotes the drift matrix, and  $\Delta t$  the time interval.

#### **Linear Stochastic Differential Equation Model:**

The measurement model is given by

$$\mathbf{y}_{i,t} = \boldsymbol{\nu} + \boldsymbol{\Lambda} \boldsymbol{\eta}_{i,t} + \boldsymbol{\varepsilon}_{i,t}, \quad \text{with} \quad \boldsymbol{\varepsilon}_{i,t} \sim \mathcal{N}\left(\mathbf{0}, \boldsymbol{\Theta}\right)$$

where  $\mathbf{y}_{i,t}$ ,  $\boldsymbol{\eta}_{i,t}$ , and  $\boldsymbol{\varepsilon}_{i,t}$  are random variables and  $\boldsymbol{\nu}$ ,  $\boldsymbol{\Lambda}$ , and  $\boldsymbol{\Theta}$  are model parameters.  $\mathbf{y}_{i,t}$  represents a vector of observed random variables,  $\boldsymbol{\eta}_{i,t}$  a vector of latent random variables, and  $\boldsymbol{\varepsilon}_{i,t}$  a vector of random measurement errors, at time t and individual i.  $\boldsymbol{\nu}$  denotes a vector of intercepts,  $\boldsymbol{\Lambda}$  a matrix of factor loadings, and  $\boldsymbol{\Theta}$  the covariance matrix of  $\boldsymbol{\varepsilon}$ .

An alternative representation of the measurement error is given by

$$\boldsymbol{\varepsilon}_{i,t} = \boldsymbol{\Theta}^{\frac{1}{2}} \mathbf{z}_{i,t}, \quad \text{with} \quad \mathbf{z}_{i,t} \sim \mathcal{N}\left(\mathbf{0}, \mathbf{I}\right)$$

where  $\mathbf{z}_{i,t}$  is a vector of independent standard normal random variables and  $\left(\Theta^{\frac{1}{2}}\right)\left(\Theta^{\frac{1}{2}}\right)' = \Theta$ . The dynamic structure is given by

$$\mathrm{d}\boldsymbol{\eta}_{i,t} = \left(\boldsymbol{\iota} + \boldsymbol{\Phi}\boldsymbol{\eta}_{i,t}\right) \mathrm{d}t + \boldsymbol{\Sigma}^{\frac{1}{2}} \mathrm{d}\mathbf{W}_{i,t}$$

where  $\iota$  is a term which is unobserved and constant over time,  $\Phi$  is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations,  $\Sigma$  is the matrix of volatility or randomness in the process, and  $\mathrm{d}W$  is a Wiener process or Brownian motion, which represents random fluctuations.

#### Value

Returns an object of class ctmedeffect which is a list with the following elements:

call Function call.

args Function arguments.

**fun** Function used ("Total").

output The matrix of total effects.

### Author(s)

Ivan Jacob Agaloos Pesigan

#### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

142 TotalCentral

### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), TotalCentral(), TotalStd(), Trajectory()

# Examples

```
phi <- matrix(</pre>
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
)
colnames(phi) \leftarrow rownames(phi) \leftarrow c("x", "m", "y")
delta_t <- 1
Total(
  phi = phi,
  delta_t = delta_t
phi <- matrix(</pre>
  data = c(
    -6, 5.5, 0, 0,
    1.25, -2.5, 5.9, -7.3,
    0, 0, -6, 2.5,
    5, 0, 0, -6
  ),
  nrow = 4
)
colnames(phi) <- rownames(phi) <- paste0("y", 1:4)</pre>
Total(
  phi = phi,
  delta_t = delta_t
)
```

TotalCentral

Total Effect Centrality

### Description

**Total Effect Centrality** 

TotalCentral 143

### Usage

```
TotalCentral(phi, delta_t, tol = 0.01)
```

### **Arguments**

tol

phi	Numeric matrix. The drift matrix $(\Phi)$ , phi should have row and column names pertaining to the variables in the system.
delta_t	Vector of positive numbers. Time interval $(\Delta t)$ .

Numeric. Smallest possible time interval to allow.

#### **Details**

The total effect centrality of a variable is the sum of the total effects of a variable on all other variables at a particular time interval.

#### Value

Returns an object of class ctmedmed which is a list with the following elements:

```
call Function call.args Function arguments.fun Function used ("TotalCentral").output A matrix of total effect centrality.
```

#### Author(s)

Ivan Jacob Agaloos Pesigan

### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

### See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalStd(), Trajectory()
```

144 TotalStd

### **Examples**

```
phi <- matrix(</pre>
 data = c(
   -0.357, 0.771, -0.450,
   0.0, -0.511, 0.729,
   0, 0, -0.693
 ),
 nrow = 3
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
# Specific time interval ------
TotalCentral(
 phi = phi,
 delta_t = 1
)
# Range of time intervals ------
total_central <- TotalCentral(</pre>
 phi = phi,
 delta_t = 1:30
plot(total_central)
# Methods ------
# TotalCentral has a number of methods including
# print, summary, and plot
total_central <- TotalCentral(</pre>
 phi = phi,
 delta_t = 1:5
print(total_central)
summary(total_central)
plot(total_central)
```

TotalStd

Standardized Total Effect Matrix Over a Specific Time Interval

### **Description**

This function computes the standardized total effects matrix over a specific time interval  $\Delta t$  using the first-order stochastic differential equation model's drift matrix  $\Phi$  and process noise covariance matrix  $\Sigma$ .

### Usage

```
TotalStd(phi, sigma, delta_t)
```

TotalStd 145

### Arguments

phi	Numeric matrix. The drift matrix $(\Phi)$ , phi should have row and column names pertaining to the variables in the system.
sigma	Numeric matrix. The process noise covariance matrix $(\Sigma)$ .
delta_t	Numeric. Time interval ( $\Delta t$ ).

#### **Details**

The standardized total effect matrix over a specific time interval  $\Delta t$  is given by

$$\operatorname{Total}_{\Delta t}^* = \mathbf{S} \left( \exp \left( \Delta t \mathbf{\Phi} \right) \right) \mathbf{S}^{-1}$$

where  $\Phi$  denotes the drift matrix, S a diagonal matrix with model-implied standard deviations on the diagonals and  $\Delta t$  the time interval.

#### Value

Returns an object of class ctmedeffect which is a list with the following elements:

call Function call.

args Function arguments.

fun Function used ("TotalStd").

output The standardized matrix of total effects.

### Author(s)

Ivan Jacob Agaloos Pesigan

### References

Bollen, K. A. (1987). Total, direct, and indirect effects in structural equation models. Sociological Methodology, 17, 37. doi:10.2307/271028

Deboeck, P. R., & Preacher, K. J. (2015). No need to be discrete: A method for continuous time mediation analysis. Structural Equation Modeling: A Multidisciplinary Journal, 23 (1), 61–75. doi:10.1080/10705511.2014.973960

Ryan, O., & Hamaker, E. L. (2021). Time to intervene: A continuous-time approach to network analysis and centrality. Psychometrika, 87 (1), 214–252. doi:10.1007/s11336021097670

#### See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), Trajectory()

Trajectory Trajectory

### **Examples**

```
phi <- matrix(</pre>
  data = c(
    -0.357, 0.771, -0.450,
    0.0, -0.511, 0.729,
    0, 0, -0.693
  ),
  nrow = 3
colnames(phi) \leftarrow rownames(phi) \leftarrow c("x", "m", "y")
sigma <- matrix(</pre>
  data = c(
    0.24455556, 0.02201587, -0.05004762,
    0.02201587, 0.07067800, 0.01539456,
    -0.05004762, 0.01539456, 0.07553061
  ),
  nrow = 3
)
delta_t <- 1
TotalStd(
  phi = phi,
  sigma = sigma,
  delta_t = delta_t
```

Trajectory

Simulate Trajectories of Variables

# Description

This function simulates trajectories of variables without measurement error or process noise. Total corresponds to the total effect and Direct corresponds to the portion of the total effect where the indirect effect is removed.

### Usage

```
Trajectory(mu0, time, phi, med)
```

# Arguments

mu0	Numeric vector. Initial values of the variables.
time	Positive integer. Number of time points.
phi	Numeric matrix. The drift matrix $(\Phi)$ . phi should have row and column names pertaining to the variables in the system.
med	Character vector. Name/s of the mediator variable/s in phi.

Trajectory 147

### Value

Returns an object of class ctmedtraj which is a list with the following elements:

```
call Function call.args Function arguments.fun Function used ("Trajectory").output A data frame of simulated data.
```

#### See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootIndirectCentral(), BootMed(), BootMedStd(), BootTotalCentral(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCPhiSigma(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd()
```

```
phi <- matrix(</pre>
 data = c(
   -0.357, 0.771, -0.450,
   0.0, -0.511, 0.729,
   0, 0, -0.693
 ),
 nrow = 3
)
colnames(phi) <- rownames(phi) <- c("x", "m", "y")</pre>
traj <- Trajectory(</pre>
 mu0 = c(3, 3, -3),
 time = 150,
 phi = phi,
 med = "m"
)
plot(traj)
# Methods ------
# Trajectory has a number of methods including
# print, summary, and plot
traj <- Trajectory(</pre>
 mu0 = c(3, 3, -3),
 time = 25,
 phi = phi,
 med = "m"
)
print(traj)
summary(traj)
```

148 Trajectory

plot(traj)

# **Index**

* Continuous Time Mediation Functions	DeltaBeta, 33
BootBeta, 3	DeltaBetaStd, 36
BootBetaStd, 6	MCBeta, 69
BootIndirectCentral, 10	MCBetaStd, 72
BootMed, 14	PosteriorBeta, 108
BootMedStd, 18	* boot
BootTotalCentral, 22	BootBeta, 3
DeltaBeta, 33	BootBetaStd, 6
DeltaBetaStd, 36	BootIndirectCentral, 10
DeltaIndirectCentral, 40	BootMed, 14
DeltaMed, 43	BootMedStd, 18
DeltaMedStd, 47	BootTotalCentral, 22
DeltaTotalCentral, 51	* cTMed
Direct, 54	BootBeta, 3
DirectStd, 57	BootBetaStd, 6
ExpCov, 59	BootIndirectCentral, 10
ExpMean, 61	BootMed, 14
Indirect, 63	BootMedStd, 18
<pre>IndirectCentral, 65</pre>	BootTotalCentral, 22
IndirectStd, 67	DeltaBeta, 33
MCBeta, 69	DeltaBetaStd, 36
MCBetaStd, 72	DeltaIndirectCentral, 40
MCIndirectCentral, 77	DeltaMed, 43
MCMed, 80	DeltaMedStd, 47
MCMedStd, 84	DeltaTotalCentral, 51
MCPhi, 88	Direct, 54
MCPhiSigma, 90	DirectStd, 57
MCTotalCentral, 92	ExpCov, 59
Med, 95	ExpMean, 61
MedStd, 98	Indirect, 63
PosteriorBeta, 108	<pre>IndirectCentral, 65</pre>
PosteriorIndirectCentral, 111	IndirectStd, 67
PosteriorMed, 114	MCBeta, 69
PosteriorTotalCentral, 117	MCBetaStd, 72
Total, 140	MCIndirectCentral, 77
TotalCentral, 142	MCMed, 80
TotalStd, 144	MCMedStd, 84
Trajectory, 146	MCPhi, 88
* beta	MCPhiSigma, 90

MCTotalCentral, 92	plot.ctmedmc, 105
Med, 95	plot.ctmedmed, 106
MedStd, 98	plot.ctmedtraj, 107
PosteriorBeta, 108	print.ctmedboot, 120
PosteriorIndirectCentral, 111	print.ctmeddelta,122
PosteriorMed, 114	print.ctmedeffect, 124
PosteriorTotalCentral, 117	print.ctmedmc, 126
Total, 140	print.ctmedmcphi, 128
TotalCentral, 142	print.ctmedmed, 129
TotalStd, 144	print.ctmedtraj, 130
Trajectory, 146	summary.ctmedboot, 131
* delta	summary.ctmeddelta,134
DeltaBeta, 33	summary.ctmedmc, 136
DeltaBetaStd, 36	summary.ctmedmed, 137
DeltaIndirectCentral, 40	summary.ctmedposteriorphi, 139
DeltaMed, 43	summary.ctmedtraj, 139
DeltaMedStd, 47	* network
DeltaTotalCentral, 51	BootIndirectCentral, 10
* effects	BootTotalCentral, 22
Direct, 54	DeltaIndirectCentral, 40
DirectStd, 57	DeltaTotalCentral, 51
Indirect, 63	<pre>IndirectCentral, 65</pre>
<pre>IndirectCentral, 65</pre>	MCIndirectCentral, 77
IndirectStd, 67	MCTotalCentral, 92
Med, 95	PosteriorIndirectCentral, 111
MedStd, 98	PosteriorTotalCentral, 117
Total, 140	TotalCentral, 142
TotalCentral, 142	* path
TotalStd, 144	BootBeta, 3
Trajectory, 146	BootBetaStd, 6
* expectations	BootMed, 14
ExpCov, 59	BootMedStd, 18
ExpMean, 61	DeltaMed, 43
* mc	DeltaMedStd, 47
MCBeta, 69	MCMed,80
MCBetaStd, 72	MCMedStd, 84
MCIndirectCentral, 77	Med, 95
MCMed, 80	MedStd, 98
MCMedStd, 84	PosteriorMed, 114
	Trajectory, 146
MCPhi, 88	* posterior
MCPhiSigma, 90	PosteriorBeta, 108
MCTotalCentral, 92	PosteriorIndirectCentral, 111
* methods	PosteriorMed, 114
confint.ctmedboot, 26	PosteriorTotalCentral, 117
confint.ctmeddelta, 29	D . D O . O . IO . IO . O . O . O . O . O
confint.ctmedmc, 31	BootBeta, 3, 8, 12, 15, 20, 24, 35, 38, 42, 45,
plot.ctmedboot, 100	49, 53, 56, 58, 60, 62, 64, 66, 68, 71
nlot ctmeddelta 103	75 79 82 86 89 91 94 97 99

```
110, 112, 115, 118, 142, 143, 145,
BootBetaStd, 4, 6, 12, 15, 20, 24, 35, 38, 42,
         45, 49, 53, 56, 58, 60, 62, 64, 66, 68,
          71, 75, 79, 82, 86, 89, 91, 94, 97, 99,
          110, 112, 115, 118, 142, 143, 145,
          147
BootIndirectCentral, 4, 8, 10, 15, 20, 24,
         35, 38, 42, 45, 49, 53, 56, 58, 60, 62,
         64, 66, 68, 71, 75, 79, 82, 86, 89, 91,
         94, 97, 99, 110, 112, 115, 118, 142,
          143, 145, 147
BootMed, 4, 8, 12, 14, 20, 24, 35, 38, 42, 45,
         49, 53, 56, 58, 60, 62, 64, 66, 68, 71,
          75, 79, 82, 86, 89, 91, 94, 97, 99,
          110, 112, 115, 118, 142, 143, 145,
          147
BootMedStd, 4, 8, 12, 15, 18, 24, 35, 38, 42,
         45, 49, 53, 56, 58, 60, 62, 64, 66, 68,
          71, 75, 79, 82, 86, 89, 91, 94, 97, 99,
          110, 112, 115, 118, 142, 143, 145,
          147
BootTotalCentral, 4, 8, 12, 15, 20, 22, 35,
         38, 42, 45, 49, 53, 56, 58, 60, 62, 64,
         66, 68, 71, 75, 79, 82, 86, 89, 91, 94,
          97, 99, 110, 112, 115, 118, 142, 143,
          145, 147
confint.ctmedboot, 26
confint.ctmeddelta, 29
confint.ctmedmc, 31
DeltaBeta, 4, 8, 12, 15, 20, 24, 33, 38, 42, 45,
         49, 53, 56, 58, 60, 62, 64, 66, 68, 71,
          75, 79, 82, 86, 89, 91, 94, 97, 99,
          110, 112, 115, 118, 142, 143, 145,
          147
DeltaBetaStd, 4, 8, 12, 15, 20, 24, 35, 36, 42,
         45, 49, 53, 56, 58, 60, 62, 64, 66, 68,
          71, 75, 79, 82, 86, 89, 91, 94, 97, 99,
          110, 112, 115, 118, 142, 143, 145,
          147
DeltaIndirectCentral, 4, 8, 12, 15, 20, 24,
         35, 38, 40, 45, 49, 53, 56, 58, 60, 62,
         64, 66, 68, 71, 75, 79, 82, 86, 89, 91,
          94, 97, 99, 110, 112, 115, 118, 142,
          143, 145, 147
DeltaMed, 4, 8, 12, 15, 20, 24, 35, 38, 42, 43,
                                                        IndirectStd, 4, 8, 12, 15, 20, 24, 35, 38, 42,
```

49, 53, 56, 58, 60, 62, 64, 66, 68, 71,

```
75, 79, 82, 86, 89, 91, 94, 97, 99,
          110, 112, 115, 118, 142, 143, 145,
          147
DeltaMedStd, 4, 8, 12, 15, 20, 24, 35, 38, 42,
          45, 47, 53, 56, 58, 60, 62, 64, 66, 68,
          71, 75, 79, 82, 86, 89, 91, 94, 97, 99,
          110, 112, 115, 118, 142, 143, 145,
          147
DeltaTotalCentral, 4, 8, 12, 15, 20, 24, 35,
          38, 42, 45, 49, 51, 56, 58, 60, 62, 64,
          66, 68, 71, 75, 79, 82, 86, 89, 91, 94,
          97, 99, 110, 112, 115, 118, 142, 143,
          145, 147
Direct, 4, 8, 12, 15, 20, 24, 35, 38, 42, 45, 49,
          53, 54, 58, 60, 62, 64, 66, 68, 71, 75,
          79, 82, 86, 89, 91, 94, 97, 99, 110,
          112, 115, 118, 142, 143, 145, 147
Direct(), 15, 44, 81, 96, 115
DirectStd, 4, 8, 12, 15, 20, 24, 35, 38, 42, 45,
          49, 53, 56, 57, 60, 62, 64, 66, 68, 71,
          75, 79, 82, 86, 89, 91, 94, 97, 99,
          110, 112, 115, 118, 142, 143, 145,
          147
DirectStd(), 19, 48, 85, 98
ExpCov, 4, 8, 12, 15, 20, 24, 35, 38, 42, 45, 49,
          53, 56, 58, 59, 62, 64, 66, 68, 71, 75,
          79, 82, 86, 89, 91, 94, 97, 99, 110,
          112, 115, 118, 142, 143, 145, 147
ExpMean, 4, 8, 12, 15, 20, 24, 35, 38, 42, 45,
          49, 53, 56, 58, 60, 61, 64, 66, 68, 71,
          75, 79, 82, 86, 89, 91, 94, 97, 99,
          110, 112, 115, 118, 142, 143, 145,
Indirect, 4, 8, 12, 15, 20, 24, 35, 38, 42, 45,
          49, 53, 56, 58, 60, 62, 63, 66, 68, 71,
          75, 79, 82, 86, 89, 91, 94, 97, 99,
          110, 112, 115, 118, 142, 143, 145,
          147
Indirect(), 15, 44, 81, 96, 115
IndirectCentral, 4, 8, 12, 15, 20, 24, 35, 38,
          42, 45, 49, 53, 56, 58, 60, 62, 64, 65,
          68, 71, 75, 79, 82, 86, 89, 91, 94, 97,
          99, 110, 112, 115, 118, 142, 143,
          145, 147
IndirectCentral(), 11, 41, 78
```

45, 49, 53, 56, 58, 60, 62, 64, 66, 67,

```
112, 115, 118, 142, 143, 145, 147
          71, 75, 79, 82, 86, 89, 91, 94, 97, 99,
          110, 112, 115, 118, 142, 143, 145,
                                                        plot.ctmedboot, 100
          147
                                                        plot.ctmeddelta, 103
IndirectStd(), 19, 48, 85, 98
                                                        plot.ctmedmc, 105
MCBeta, 4, 8, 12, 15, 20, 24, 35, 38, 42, 45, 49,
                                                        plot.ctmedmed, 106
          53, 56, 58, 60, 62, 64, 66, 68, 69, 75,
                                                        plot.ctmedtraj, 107
          79, 82, 86, 89, 91, 94, 97, 99, 110,
                                                        PosteriorBeta, 4, 8, 12, 15, 20, 24, 35, 38,
          112, 115, 118, 142, 143, 145, 147
                                                                  42, 45, 49, 53, 56, 58, 60, 62, 64, 66,
MCBetaStd, 4, 8, 12, 15, 20, 24, 35, 38, 42, 45,
                                                                  68, 71, 75, 79, 82, 86, 89, 91, 94, 97,
         49, 53, 56, 58, 60, 62, 64, 66, 68, 71,
                                                                  99, 108, 112, 115, 118, 142, 143,
         72, 79, 82, 86, 89, 91, 94, 97, 99,
                                                                  145, 147
          110, 112, 115, 118, 142, 143, 145,
                                                        PosteriorIndirectCentral, 4, 8, 12, 15, 20,
          147
                                                                  24, 35, 38, 42, 45, 49, 53, 56, 58, 60,
MCIndirectCentral, 4, 8, 12, 15, 20, 24, 35,
                                                                  62, 64, 66, 68, 71, 75, 79, 82, 86, 89,
         38, 42, 45, 49, 53, 56, 58, 60, 62, 64,
                                                                  91, 94, 97, 99, 110, 111, 115, 118,
         66, 68, 71, 75, 77, 82, 86, 89, 91, 94,
                                                                  142, 143, 145, 147
         97, 99, 110, 112, 115, 118, 142, 143,
                                                        PosteriorMed, 4, 8, 12, 15, 20, 24, 35, 38, 42,
          145, 147
                                                                  45, 49, 53, 56, 58, 60, 62, 64, 66, 68,
MCMed, 4, 8, 12, 15, 20, 24, 35, 38, 42, 45, 49,
                                                                  71, 75, 79, 82, 86, 89, 91, 94, 97, 99,
          53, 56, 58, 60, 62, 64, 66, 68, 71, 75,
                                                                  110, 112, 114, 118, 142, 143, 145,
          79, 80, 86, 89, 91, 94, 97, 99, 110,
                                                                  147
          112, 115, 118, 142, 143, 145, 147
                                                        PosteriorTotalCentral, 4, 8, 12, 15, 20, 24,
MCMedStd, 4, 8, 12, 15, 20, 24, 35, 38, 42, 45,
                                                                  35, 38, 42, 45, 49, 53, 56, 58, 60, 62,
          49, 53, 56, 58, 60, 62, 64, 66, 68, 71,
                                                                  64, 66, 68, 71, 75, 79, 82, 86, 89, 91,
          75, 79, 82, 84, 89, 91, 94, 97, 99,
                                                                  94, 97, 99, 110, 112, 115, 117, 142,
          110, 112, 115, 118, 142, 143, 145,
                                                                  143, 145, 147
          147
                                                        print.ctmedboot, 120
MCPhi, 4, 8, 12, 15, 20, 24, 35, 38, 42, 45, 49,
                                                        print.ctmeddelta, 122
          53, 56, 58, 60, 62, 64, 66, 68, 71, 75,
                                                        print.ctmedeffect, 124
          79, 82, 86, 88, 91, 94, 97, 99, 110,
                                                        print.ctmedmc, 126
          112, 115, 118, 142, 143, 145, 147
                                                        print.ctmedmcphi. 128
MCPhiSigma, 4, 8, 12, 15, 20, 24, 35, 38, 42,
                                                        print.ctmedmed, 129
         45, 49, 53, 56, 58, 60, 62, 64, 66, 68,
                                                        print.ctmedtraj, 130
          71, 75, 79, 82, 86, 89, 90, 94, 97, 99,
          110, 112, 115, 118, 142, 143, 145,
                                                        summary.ctmedboot, 131
          147
                                                        summary.ctmeddelta, 134
MCTotalCentral, 4, 8, 12, 15, 20, 24, 35, 38,
                                                        summary.ctmedmc, 136
         42, 45, 49, 53, 56, 58, 60, 62, 64, 66,
                                                        summary.ctmedmed, 137
          68, 71, 75, 79, 82, 86, 89, 91, 92, 97,
                                                        summary.ctmedposteriorphi, 139
         99, 110, 112, 115, 118, 142, 143,
                                                        summary.ctmedtraj, 139
          145, 147
Med, 4, 8, 12, 15, 20, 24, 35, 38, 42, 45, 49, 53,
                                                        Total, 4, 8, 12, 15, 20, 24, 35, 38, 42, 45, 49,
                                                                  53, 56, 58, 60, 62, 64, 66, 68, 71, 75,
          56, 58, 60, 62, 64, 66, 68, 71, 75, 79,
         82, 86, 89, 91, 94, 95, 99, 110, 112,
                                                                  79, 82, 86, 89, 91, 94, 97, 99, 110,
          115, 118, 142, 143, 145, 147
                                                                  112, 115, 118, 140, 143, 145, 147
MedStd, 4, 8, 12, 15, 20, 24, 35, 38, 42, 45, 49,
                                                        Total(), 3, 15, 33, 44, 70, 81, 96, 109, 115
                                                        TotalCentral, 4, 8, 12, 15, 20, 24, 35, 38, 42,
          53, 56, 58, 60, 62, 64, 66, 68, 71, 75,
          79, 82, 86, 89, 91, 94, 97, 98, 110,
                                                                  45, 49, 53, 56, 58, 60, 62, 64, 66, 68,
```

```
71, 75, 79, 82, 86, 89, 91, 94, 97, 99, 110, 112, 115, 118, 142, 142, 145, 147

TotalCentral(), 23, 52, 93, 112, 117

TotalStd, 4, 8, 12, 15, 20, 24, 35, 38, 42, 45, 49, 53, 56, 58, 60, 62, 64, 66, 68, 71, 75, 79, 82, 86, 89, 91, 94, 97, 99, 110, 112, 115, 118, 142, 143, 144, 147

TotalStd(), 7, 19, 37, 48, 73, 85, 98

Trajectory, 4, 8, 12, 15, 20, 24, 35, 38, 42, 45, 49, 53, 56, 58, 60, 62, 64, 66, 68, 71, 75, 79, 82, 86, 89, 91, 94, 97, 99, 110, 112, 115, 118, 142, 143, 145, 146
```