Package 'cTMed'

December 30, 2024
Title Continuous Time Mediation
Version 1.0.4
Description 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>
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Description

This function generates a bootstrap method sampling distribution for the elements of the matrix of lagged coefficients β over a specific time interval Δt or a range of time intervals using the first-order stochastic differential equation model drift matrix Φ .

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 (Φ) .
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 (Δt).
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.

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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(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

```
## Not run:
library(simStateSpace)
# 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))
```

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```
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 = 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) <- 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

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 β over a specific time interval Δt or a range of time intervals using the first-order stochastic differential equation model drift matrix Φ .

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 (Φ) .
sigma	List of numeric matrices. Each element of the list is a bootstrap estimate of the process noise covariance matrix (Σ) .
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 (Δt).
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.

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(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCPhi(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

```
## Not run:
library(simStateSpace)
# 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 = 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_1 = theta_1,
  ncores = parallel::detectCores() - 1,
  seed = 42
phi_hat <- phi
colnames(phi_hat) <- rownames(phi_hat) <- c("x", "m", "y")</pre>
sigma_hat <- sigma
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
)
```

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```
# 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
# 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)
```

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 Δt 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 (Φ) .
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 (Δt).

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from	Character string. Name of the independent variable X in phi.
to	Character string. Name of the dependent variable Y in \mbox{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 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(), BootMedStd(), DeltaBeta(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCPhi(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

BootMed BootMed

```
## Not run:
library(simStateSpace)
# 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,
```

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```
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 = 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 ------
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 Δt 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 (Φ) .

sigma	List of numeric matrices. Each element of the list is a bootstrap estimate of the process noise covariance matrix (Σ) .
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 (Δt).
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(), BootMed(), DeltaBeta(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCPhi(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

```
## Not run:
library(simStateSpace)
# 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 = 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_1 = theta_1,
 ncores = parallel::detectCores() - 1,
 seed = 42
phi_hat <- phi
colnames(phi_hat) <- rownames(phi_hat) <- c("x", "m", "y")</pre>
sigma_hat <- sigma
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^{*},
```

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```
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)
```

confint.ctmedboot

Monte Carlo Method Confidence Intervals

Description

Monte Carlo 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 considered.

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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.

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) \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,
```

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```
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
confint(mc, level = 0.95)
# 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
confint(mc, level = 0.95)
```

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 considered.

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

Value

Returns a data frame of 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,
   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
 ),
```

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```
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(delta, level = 0.95)
# 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"
)
confint(delta, level = 0.95)
```

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 consid-

ered.

level the confidence level required.

... additional arguments.

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Value

Returns a data frame of 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,
    -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
)
```

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```
# 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
)
confint(mc, level = 0.95)
# 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
)
confint(mc, level = 0.95)
```

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 β over a specific time interval Δt or a range of time intervals using the first-order stochastic differential equation model's drift matrix Φ .

Usage

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

Arguments

phi	Numeric matrix. The drift matrix (Φ) , 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 (Δt) .
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.

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Details

See Total().

Delta Method:

Let θ be $\text{vec}(\Phi)$, that is, the elements of the Φ 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 θ and Γ 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 Γ 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 ("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

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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(), BootMedStd(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), 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,
    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 β over a specific time interval Δt or a range of time intervals using the first-order stochastic differential equation model's drift matrix Φ and process noise covariance matrix Σ .

Usage

```
DeltaBetaStd(phi, sigma, vcov_theta, delta_t, ncores = NULL, tol = 0.01)
```

Arguments

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

Sigma Numeric matrix. The process noise covariance matrix (Σ) .

VCOV_theta Numeric matrix. The sampling variance-covariance matrix of $\operatorname{vec}(\Phi)$ and $\operatorname{vech}(\Sigma)$ delta_t Numeric. Time interval (Δt) .

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().

Delta Method:

Let θ be a vector that combines $\operatorname{vec}(\Phi)$, that is, the elements of the Φ matrix in vector form sorted column-wise and $\operatorname{vech}(\Sigma)$, that is, the unique elements of the Σ matrix in vector form sorted column-wise. Let $\hat{\theta}$ be a vector that combines $\operatorname{vec}(\hat{\Phi})$ and $\operatorname{vech}(\hat{\Sigma})$. 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 θ and Γ 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 Γ 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 ("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(), BootMed(), BootMedStd(), DeltaBeta(), DeltaIndirectCentral(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), 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")
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(
 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,
   \hbox{-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 -------
DeltaBetaStd(
```

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```
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 Δt or a range of time intervals using the first-order stochastic differential equation model's drift matrix Φ .

Usage

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

Arguments

phi	Numeric matrix. The drift matrix (Φ) , 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 (Δt) .
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.

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Details

See IndirectCentral() more details.

Delta Method:

Let θ be $\operatorname{vec}(\Phi)$, that is, the elements of the Φ 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 θ and Γ 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 Γ 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 ("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.

Author(s)

Ivan Jacob Agaloos Pesigan

DeltaIndirectCentral 33

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(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), 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,
```

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```
-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)
# 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 mediator variables \mathbf{m} over a specific time interval Δt 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)
```

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Arguments

Numeric matrix. The drift matrix (Φ) , 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 (Φ) .

delta_t Vector of positive numbers. Time interval (Δt) .

from Character string. Name of the dependent 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 θ be $\operatorname{vec}(\Phi)$, that is, the elements of the Φ matrix in vector form sorted column-wise. Let $\hat{\theta}$ be $\operatorname{vec}(\hat{\Phi})$. By the multivariate central limit theory, the function 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 θ and Γ 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 Γ 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 ("DeltaMed").

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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(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMedStd(), MCPhi(), 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")
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,
    -0.00022, -0.00273, -0.00016,</pre>
```

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```
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"
)
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)
```

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

Delta Method:

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

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.

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(), BootMedStd(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCPhi(), 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 ------
DeltaMedStd(
 phi = phi,
 sigma = sigma,
 vcov_theta = vcov_theta,
 delta_t = 1,
 from = "x",
 to = "y",
 med = "m"
)
# Range of time intervals -------
delta <- DeltaMedStd(
 phi = phi,
 sigma = sigma,
```

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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 Δt or a range of time intervals using the first-order stochastic differential equation model's drift matrix Φ .

Usage

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

Arguments

phi	Numeric matrix. The drift matrix (Φ) , 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 (Δt) .
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.

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Delta Method:

Let θ be $\text{vec}(\Phi)$, that is, the elements of the Φ 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 θ and Γ 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 Γ 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

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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(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), 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,
    0.00324, 0.00009, -0.00050,
```

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```
-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 Δt using the first-order stochastic differential equation model's drift matrix $\mathbf{\Phi}$.

Usage

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

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Arguments

phi	Numeric matrix. The drift matrix (Φ) . phi should have row and column names pertaining to the variables in the system.
delta_t	Numeric. Time interval (Δt).
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 Φ 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 Φ , j the column index of X in Φ , and Δt the time interval.

Linear Stochastic Differential Equation Model:

The measurement model is given by

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

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 ι is a term which is unobserved and constant over time, Φ is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations, Σ 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.

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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(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), 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
)
```

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```
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 Δt 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 (Φ) , phi should have row and column names pertaining to the variables in the system.
sigma	Numeric matrix. The process noise covariance matrix (Σ) .
delta_t	Numeric. Time interval (Δt).
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 Φ 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 Φ , j the column index of X in Φ , \mathbf{S} a diagonal matrix with model-implied standard deviations on the diagonals, and Δt the time interval.

DirectStd 49

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(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), 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
),
  nrow = 3</pre>
```

50 ExpCov

```
)
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 Δt 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

$$eta_{\Delta t} = \exp\left(\Delta t \mathbf{\Phi}\right),$$
 $oldsymbol{\Psi}_{\Delta t} = \mathbf{\Phi}^{\#} \left(\exp\left(\Delta t \mathbf{\Phi}\right) - \mathbf{J}\right) \operatorname{vec}\left(\mathbf{\Sigma}\right), \quad ext{and}$
 $oldsymbol{\Phi}^{\#} = \left(\mathbf{\Phi} \otimes \mathbf{I}\right) + \left(\mathbf{I} \otimes \mathbf{\Phi}\right).$

Note that I and J are identity matrices.

Usage

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

Arguments

phi	Numeric matrix. The drift matrix (Φ) . phi should have row and column names
	pertaining to the variables in the system.
sigma	Numeric matrix. The process noise covariance matrix (Σ) .
delta_t	Numeric. Time interval (Δt).

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

ExpCov 51

 $\varepsilon_{i,t}$ a vector of random measurement errors, at time t and individual i. ν denotes a vector of intercepts, Λ a matrix of factor loadings, and Θ the covariance matrix of ε .

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 ι is a term which is unobserved and constant over time, Φ is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations, Σ 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(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), 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>
```

52 ExpMean

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

ExpMean

Model-Implied State Mean Vector

Description

The function returns the model-implied state mean vector for a particular time interval Δt given by

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 (Φ), 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 (ι).
delta_t	Numeric. Time interval (Δt).

Details

Linear Stochastic Differential Equation Model:

The measurement model is given by

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

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 ε .

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An alternative representation of the measurement error is given by

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

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 ι is a term which is unobserved and constant over time, Φ is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations, Σ 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(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), 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")
iota <- c(.5, .3, .4)
delta_t <- 1
ExpMean(
  phi = phi,
  iota = iota,
  delta_t = delta_t
)
```

54 Indirect

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 Δt 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 (Φ). phi should have row and column names pertaining to the variables in the system.
delta_t	Numeric. Time interval (Δt).
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 Δt is given by

Indirect_{$$\Delta t_{i,j}$$} = exp $(\Delta t \mathbf{\Phi})_{i,j}$ - exp $(\Delta t \mathbf{D_m} \mathbf{\Phi} \mathbf{D_m})_{i,j}$

where Φ 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 Φ , j the column index of X in Φ , and Δt 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 ε .

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 $\left(\mathbf{\Theta}^{\frac{1}{2}}\right)\left(\mathbf{\Theta}^{\frac{1}{2}}\right)' = \mathbf{\Theta}$.

Indirect 55

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 ι is a term which is unobserved and constant over time, Φ is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations, Σ 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(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), 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>
```

56 IndirectCentral

```
nrow = 3
)
colnames(phi) \leftarrow rownames(phi) \leftarrow c("x", "m", "y")
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 (Φ) , phi should have row and column names pertaining to the variables in the system.
delta_t	Vector of positive numbers. Time interval (Δt) .
tol	Numeric. Smallest possible time interval to allow.

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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(), BootMed(), BootMedStd(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

58 IndirectStd

```
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 Δt 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 (Φ) . phi should have row and column names pertaining to the variables in the system.
sigma	Numeric matrix. The process noise covariance matrix (Σ) .
delta_t	Numeric. Time interval (Δt).
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.

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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 Δt is given by

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

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

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(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMedStd(), MCPhi(), 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>
```

60 MCBeta

```
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
)
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 β over a specific time interval Δt or a range of time intervals using the first-order stochastic differential equation model drift matrix Φ .

Usage

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

Arguments

phi

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

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vcov_phi_vec Numeric matrix. The sampling variance-covariance matrix of vec (Φ) .

delta_t Numeric. Time interval (Δt).

R Positive integer. Number of replications.

test_phi Logical. If test_phi = TRUE, the function tests the stability of the generated

drift matrix Φ . If the test returns FALSE, the function generates a new drift

matrix Φ 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 θ be $\operatorname{vec}(\Phi)$, that is, the elements of the Φ 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.

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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(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), 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
)
# 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)
```

 ${\tt MCBetaStd}$

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

Description

This function generates a Monte Carlo method sampling distribution for the elements of the standardized matrix of lagged coefficients β over a specific time interval Δt or a range of time intervals using the first-order stochastic differential equation model drift matrix Φ and process noise covariance matrix Σ .

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 (Φ) . phi should have row and column names pertaining to the variables in the system.
sigma	Numeric matrix. The process noise covariance matrix (Σ) .
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 (Δt) .
R	Positive integer. Number of replications.
test_phi	Logical. If test_phi = TRUE, the function tests the stability of the generated drift matrix Φ . If the test returns FALSE, the function generates a new drift matrix Φ 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 θ be a vector that combines $\operatorname{vec}(\Phi)$, that is, the elements of the Φ matrix in vector form sorted column-wise and $\operatorname{vech}(\Sigma)$, that is, the unique elements of the Σ 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

See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), 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")
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 -------
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)
plot(mc)
```

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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 Δt using the first-order stochastic differential equation model drift matrix Φ .

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 (Φ) , 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 (Δt) .
R	Positive integer. Number of replications.
test_phi	Logical. If test_phi = TRUE, the function tests the stability of the generated drift matrix Φ . If the test returns FALSE, the function generates a new drift matrix Φ 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:

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Let θ be $\operatorname{vec}(\Phi)$, that is, the elements of the Φ 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

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See Also

Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCMed(), MCPhi(), 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
)
```

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```
# 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 Δt 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,
```

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

Arguments

phi Numeric matrix. The drift matrix (Φ) , 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 (Δt).

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 Φ . If the test returns FALSE, the function generates a new drift

matrix Φ 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 θ be $\operatorname{vec}(\Phi)$, that is, the elements of the Φ 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.

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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(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMedStd(), MCPhi(), 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")
vcov_phi_vec <- matrix(</pre>
```

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```
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 Δt 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

phi	Numeric matrix. The drift matrix (Φ). phi should have row and column names
	pertaining to the variables in the system.
sigma	Numeric matrix. The process noise covariance matrix (Σ) .
vcov_theta	Numeric matrix. The sampling variance-covariance matrix of $\operatorname{vec}\left(\Phi\right)$ and $\operatorname{vech}\left(\Sigma\right)$
delta_t	Numeric. Time interval (Δt).
from	Character string. Name of the independent variable <i>X</i> 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 Φ . If the test returns FALSE, the function generates a new drift matrix Φ 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(), DirectStd(), and IndirectStd() for more details.

Monte Carlo Method:

Let θ be a vector that combines $\operatorname{vec}(\Phi)$, that is, the elements of the Φ matrix in vector form sorted column-wise and $\operatorname{vech}(\Sigma)$, that is, the unique elements of the Σ 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 ("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(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCPhi(), 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
```

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```
# 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)
# 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 Φ 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 (Φ) , 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 Φ . If the test returns FALSE, the function generates a new drift matrix Φ 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

Details

Monte Carlo Method:

Let θ be $\operatorname{vec}(\Phi)$, that is, the elements of the Φ 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(), BootMed(), BootMedStd(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), 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")
MCPhi(</pre>
```

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```
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
)
```

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 Δt using the first-order stochastic differential equation model drift matrix Φ .

Usage

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

Arguments

phi

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

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vcov_phi_vec Numeric matrix. The sampling variance-covariance matrix of vec (Φ) .

delta_t Numeric. Time interval (Δt).

R Positive integer. Number of replications.

test_phi Logical. If test_phi = TRUE, the function tests the stability of the generated

drift matrix Φ . If the test returns FALSE, the function generates a new drift

matrix Φ 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 θ be $\operatorname{vec}(\Phi)$, that is, the elements of the Φ 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.

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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(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), 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,
```

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```
-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 Δt or a range of

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

Usage

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

Arguments

phi	Numeric matrix. The drift matrix (Φ) . phi should have row and column names pertaining to the variables in the system.
delta_t	Vector of positive numbers. Time interval (Δt).
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

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

where $\mathbf{y}_{i,t}$, $\boldsymbol{\eta}_{i,t}$, 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

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

where ι is a term which is unobserved and constant over time, Φ is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations, Σ 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.

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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(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), 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",
 med = "m"
```

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```
plot(med)

# Methods ------
# Med has a number of methods including
# print, summary, and plot
med <- Med(
   phi = phi,
   delta_t = 1:5,
   from = "x",
   to = "y",
   med = "m"
)
print(med)
summary(med)
plot(med)</pre>
```

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 Δt 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 (Φ) , phi should have row and column names pertaining to the variables in the system.
sigma	Numeric matrix. The process noise covariance matrix (Σ) .
delta_t	Numeric. Time interval (Δt) .
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.

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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(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), 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
),
  nrow = 3</pre>
```

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```
)
# 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", ...)
```

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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

```
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,
    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,
```

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```
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.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.

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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,
   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,
```

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```
from = "x",
  to = "y",
  med = "m"
)
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(</pre>
```

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```
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 ------
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

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Usage

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

Arguments

x 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

```
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)
```

96 plot.ctmedtraj

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, ...)
```

Arguments

x 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

```
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"
)

plot(traj)</pre>
```

PosteriorBeta 97

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 β over a specific time interval Δt or a range of time intervals using the first-order stochastic differential equation model drift matrix Φ .

Usage

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

Arguments

phi	Numeric matrix. The drift matrix (Φ) , phi should have row and column names pertaining to the variables in the system.
delta_t	Numeric. Time interval (Δt) .
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

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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(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCTotalCentral(), Med(), MedStd(), 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,
    0.00324, 0.00009, -0.00050,
```

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```
-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 ------
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 Δt or a range of time intervals using the posterior distribution of the first-order stochastic differential equation model drift matrix Φ .

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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 (Φ). Each matrix should have row and column

names pertaining to the variables in the system.

delta_t Numeric. Time interval (Δt).

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

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See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), 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,
    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
)
```

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

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 Δt or a range of time intervals using the posterior distribution of the first-order stochastic differential equation model drift matrix Φ .

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 (Φ). Each matrix should have row and column names pertaining to the variables in the system.
delta_t	Numeric. Time interval (Δt).
from	Character string. Name of the independent variable X in phi.

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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 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(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd(), Trajectory()
```

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```
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 ------
PosteriorMed(
  phi = phi,
```

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

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 Δt or a range of time intervals using the posterior distribution of the first-order stochastic differential equation model drift matrix Φ .

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 (Φ). Each matrix should have row and column names pertaining to the variables in the system.
delta_t	Numeric. Time interval (Δt) .
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.

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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 ("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(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), 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</pre>
```

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```
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
)
phi <- MCPhi(</pre>
 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
```

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```
# Methods ------
# PosteriorTotalCentral has a number of methods including
# print, summary, confint, and plot
print(posterior)
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 α.
    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 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
),</pre>
```

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```
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
)
# 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,
```

print.ctmeddelta

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

print.ctmeddelta

Print Method for Object of Class ctmeddelta

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(
  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(</pre>
```

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```
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
)
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.ctmedeffect

Print Method for Object of Class ctmedeffect

Description

Print Method for Object of Class ctmedeffect

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)
```

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

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

Х	an object of class ctmedmc.
alpha	Numeric vector. Significance level α .
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

print.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",
```

print.ctmedmcphi 115

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

print.ctmedmed

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) \leftarrow rownames(phi) \leftarrow c("x", "m", "y")
mc <- MCPhi(</pre>
  phi = phi,
  vcov_phi_vec = 0.1 * diag(9),
  R = 100L # use a large value for R in actual research
)
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

print.ctmedtraj 117

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

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.

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Value

Prints 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"
)

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 α .
type	Charater string. Confidence interval type, that is, type = "pc" for percentile; type = "bc" for bias corrected.
	additional arguments.

summary.ctmedboot 119

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,
    -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
)
```

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```
# 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 \text{ \# use a large value for } R \text{ 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)
```

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 α additional arguments.

Value

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

summary.ctmeddelta 121

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,
   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,
```

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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 α .
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

summary.ctmedmc 123

```
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",
```

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```
R = 100L # use a large value for R in actual research
)
summary(mc)

# 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
)
summary(mc)</pre>
```

summary.ctmedmed

Summary Method for an Object of Class 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

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")
# Specific time interval ------
med <- Med(</pre>
 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.
```

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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.
```

Value

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

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

Total 127

```
med = "m"
)
summary(traj)
```

Total

Total Effect Matrix Over a Specific Time Interval

Description

This function computes the total effects matrix over a specific time interval Δt using the first-order stochastic differential equation model's drift matrix Φ .

Usage

Total(phi, delta_t)

Arguments

phi

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

delta_t

Numeric. Time interval (Δt).

Details

The total effect matrix over a specific time interval Δt is given by

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

where Φ denotes the drift matrix, and Δt 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 $\mathbf{y}_{i,t}$, $\eta_{i,t}$, and $\varepsilon_{i,t}$ are random variables and ν , Λ , and Θ 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. ν denotes a vector of intercepts, Λ a matrix of factor loadings, and Θ the covariance matrix of ε .

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

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

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where ι is a term which is unobserved and constant over time, Φ is the drift matrix which represents the rate of change of the solution in the absence of any random fluctuations, Σ 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

See Also

```
Other Continuous Time Mediation Functions: BootBeta(), BootBetaStd(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCMedStd(), MCPhi(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), 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")
delta_t <- 1</pre>
```

TotalCentral 129

```
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

Usage

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

Arguments

phi	Numeric matrix. The drift matrix (Φ) . phi should have row and column names pertaining to the variables in the system.
delta_t	Vector of positive numbers. Time interval (Δt).
tol	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.

TotalCentral

```
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(), BootMed(), BootMedStd(), DeltaBeta(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCPhi(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), 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 ------
TotalCentral(
 phi = phi,
 delta_t = 1
# Range of time intervals ------
total_central <- TotalCentral(</pre>
 phi = phi,
 delta_t = 1:30
)
```

TotalStd 131

```
# Methods ------
# TotalCentral has a number of methods including
# print, summary, and plot
total_central <- TotalCentral(
   phi = phi,
   delta_t = 1:5
)
print(total_central)
summary(total_central)
plot(total_central)</pre>
```

TotalStd

Standardized Total Effect Matrix Over a Specific Time Interval

Description

This function computes the standardized total effects matrix over a specific time interval Δt using the first-order stochastic differential equation model's drift matrix Φ and process noise covariance matrix Σ .

Usage

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

Arguments

phi	Numeric matrix. The drift matrix (Φ) , phi should have row and column names
	pertaining to the variables in the system.
sigma	Numeric matrix. The process noise covariance matrix (Σ) .
delta_t	Numeric. Time interval (Δt).

Details

The standardized total effect matrix over a specific time interval Δt is given by

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

where Φ denotes the drift matrix, S a diagonal matrix with model-implied standard deviations on the diagonals and Δt 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.
```

TotalStd TotalStd

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(), BootMedStd(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCPhi(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), 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")
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 133

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 (Φ). 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.

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(), BootMed(), BootMed(), BootMedStd(), DeltaBetaStd(), DeltaIndirectCentral(), DeltaMed(), DeltaMedStd(), DeltaTotalCentral(), Direct(), DirectStd(), ExpCov(), ExpMean(), Indirect(), IndirectCentral(), IndirectStd(), MCBeta(), MCBetaStd(), MCIndirectCentral(), MCMed(), MCPhi(), MCTotalCentral(), Med(), MedStd(), PosteriorBeta(), PosteriorIndirectCentral(), PosteriorMed(), PosteriorTotalCentral(), Total(), TotalCentral(), TotalStd()
```

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

Trajectory Trajectory

```
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)
# 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)
plot(traj)
```

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