

# Package ‘germinationmetrics’

February 9, 2020

**Title** Seed Germination Indices and Curve Fitting

**Version** 0.1.3.9000

**Description** Provides functions to compute various germination indices such as germinability, median germination time, mean germination time, mean germination rate, speed of germination, Timson's index, germination value, coefficient of uniformity of germination, uncertainty of germination process, synchrony of germination etc. from germination count data. Includes functions for fitting cumulative seed germination curves using four-parameter hill function and computation of associated parameters. See the vignette for more, including full list of citations for the methods implemented.

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**VignetteBuilder** knitr

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ggplot2,  
ggrepel,  
minpack.lm,  
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utils,  
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**Suggests** knitr,  
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httr,  
RCurl

**RdMacros** Rdpack

**URL** <https://github.com/aravind-j/germinationmetrics>,  
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<https://CRAN.R-project.org/package=germinationmetrics>  
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**BugReports** <https://github.com/aravind-j/germinationmetrics/issues>

**R topics documented:**

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|        |   |
|--------|---|
| CUGerm | <i>Coefficient of uniformity of germination</i> |
|--------|---|

---

**Description**

Compute the Coefficient of uniformity of germination (CUG).

**Usage**

CUGerm(germ.counts, intervals, partial = TRUE)

**Arguments**

|             |   |
|-------------|---|
| germ.counts | Germination counts at each time interval. Can be partial or cumulative as specified in the argument partial.          |
| intervals   | The time intervals.   |
| partial     | logical. If TRUE, germ.counts is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE. |

## Details

CUG is computed as follows (Heydecker 1972; Bewley and Black 1994).

$$CUG = \frac{\sum_{i=1}^k N_i}{\sum_{i=1}^k (\bar{T} - T_i)^2 N_i}$$

Where,  $\bar{T}$  is the mean germination time,  $T_i$  is the time from the start of the experiment to the  $i$ th interval,  $N_i$  is the number of seeds germinated in the  $i$ th time interval (not the accumulated number, but the number corresponding to the  $i$ th interval), and  $k$  is the total number of time intervals.

## Value

The value of the coefficient of uniformity of germination as  $\text{time}^{-2}$ .

## References

Bewley JD, Black M (1994). *Seeds: Physiology of Development and Germination..* Plenum Publishing Corporation, New York, USA. ISBN 0-306-44748-7.

Heydecker W (1972). *Seed Ecology. Proceedings of the Nineteenth Easter School in Agricultural Science, University of Nottingham, 1972.* Pennsylvania State University Press, University Park, USA.

## See Also

[GermSynchrony](#), [MeanGermTime](#)

## Examples

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)

# From partial germination counts
#-----
CUGerm(germ.counts = x, intervals = int)

# From cumulative germination counts
#-----
CUGerm(germ.counts = y, intervals = int, partial = FALSE)
```

---

|                    |   |
|--------------------|---|
| EmergenceRateIndex | <i>Emergence Rate Index or Germination Rate Index</i> |
|--------------------|---|

---

## Description

Compute the Emergence rate index or Germination rate index according to

- Shmueli and Goldberg (1971) and it's modification by de Santana and Ranal (2004) (Ranal and de Santana 2006);
- Bilbro and Wanjura (1982); and
- Fakorede and Ayoola (1980), Fakorede and Ojo (1981), and Fakorede and Agbana (1983).

### Usage

```
EmergenceRateIndex(
  germ.counts,
  intervals,
  partial = TRUE,
  total.seeds = NULL,
  method = c("melville", "melvillessantanaranal", "bilbrowanjura", "fakorede")
)
```

### Arguments

|             |  |
|-------------|--|
| germ.counts | Germination counts at each time interval. Can be partial or cumulative as specified in the argument partial.                                   |
| intervals   | The time intervals.  |
| partial     | logical. If TRUE, germ.counts is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE.                          |
| total.seeds | Total number of seeds.   |
| method      | The method to be used. Either "melville", "melvillessantanaranal", "bilbrowanjura" or "fakorede". Default is "melville" (see <b>Details</b> ). |

### Value

The value of the Emergence rate index.

### Details

Several germination indices are referred to as Emergence rate Index (*ERI*).

**Shmueli and Goldberg (1971):** It is estimated as follows.

$$ERI = \sum_{i=i_0}^{k-1} N_i(k-i)$$

Where,  $N_i$  is the number of seeds germinated in the  $i$ th time interval (not the accumulated number, but the number corresponding to the  $i$ th interval),  $i_0$  is the time interval when emergence/germination started, and  $k$  is the total number of time intervals.

A modification for the same was suggested by de Santana and Ranal (2004) (Ranal and de Santana 2006) and is estimated by dividing Emergence rate index (*ERI*) by total number of emerged seedlings (or germinated seeds) as follows.

$$ERI_{mod} = \frac{\sum_{i=i_0}^{k-1} N_i(k-i)}{N_g} = \frac{ERI}{N_g}$$

Where,  $N_g$  is the total number of germinated seeds at the end of the test,  $N_i$  is the number of seeds germinated in the  $i$ th time interval (not the accumulated number, but the number corresponding to the  $i$ th interval),  $i_0$  is the time interval when emergence/germination started, and  $k$  is the total number of time intervals.

**Bilbro and Wanjura (1982):** It is the estimated as follows.

$$ERI = \frac{\sum_{i=1}^k N_i}{T} = \frac{N_g}{T}$$

Where,  $N_g$  is the total number of germinated seeds at the end of the test,  $N_i$  is the number of seeds germinated in the  $i$ th time interval (not the accumulated number, but the number corresponding to the  $i$ th interval), and  $\bar{T}$  is the mean germination time or mean emergence time.

**Fakorede and Ayoola (1980); Fakorede and Ojo (1981); Fakorede and Agbana (1983):** It is estimated as follows.

$$ERI = \frac{\bar{T}}{FGP/100}$$

Where,  $\bar{T}$  is the Mean germination time and  $FGP$  is the final germination time.

**Others:** Apart from the above the above, the name Emergence rate index ( $ERI$ ) has also been used to for the mathematical expressions for Speed of germination ([GermSpeed](#)) (Allan et al. 1962; Erbach 1982), Timson's index ([TimsonsIndex](#)) (Chaudhary and Ghildyal 1970), and George's index ([GermRateGeorge](#)) (Chopra and Chaudhary 1980).

## References

- Allan RE, Vogel OA, Peterson CJ (1962). "Seedling emergence rate of fall-sown wheat and its association with plant height and coleoptile length." *Agronomy Journal*, **54**(4), 347.
- Bilbro JD, Wanjura DF (1982). "Soil crusts and cotton emergence relationships." *Transactions of the ASAE*, **25**(6), 1484–1487.
- Chaudhary TN, Ghildyal BP (1970). "Effect of temperature associated with levels of bulk density on rice seedling emergence." *Plant and Soil*, **33**(1), 87–90.
- Chopra UK, Chaudhary TN (1980). "Effect of soil temperature alteration by soil covers on seedling emergence of wheat (*Triticum aestivum* L.) sown on two dates." *Plant and Soil*, **57**(1), 125–129.
- Erbach DC (1982). "Tillage for continuous corn and corn-soybean rotation." *Transactions of the ASAE*, **25**(4), 906–911.
- Fakorede MAB, Agbana SB (1983). "Heterotic effects and association of seedling vigour with mature characteristics and grain yield in some tropical maize cultivars." *Maydica*, **28**, 327–338.
- Fakorede MAB, Ayoola AO (1980). "Relation between seedling vigor and selection for yield improvement in maize." *Maydica*, **25**(3), 135–147.
- Fakorede MAB, Ojo DK (1981). "Variability for seedling vigour in maize." *Experimental Agriculture*, **17**(2), 195–201.
- Ranal MA, de Santana DG (2006). "How and why to measure the germination process?" *Brazilian Journal of Botany*, **29**(1), 1–11.
- Shmueli M, Goldberg D (1971). "Emergence, early growth, and salinity of five vegetable crops germinated by sprinkle and trickle irrigation in an arid zone." *HortScience*, **6**, 563–565.
- de Santana DG, Ranal MA (2004). *Análise Da Germinação: Um Enfoque Estatístico*. Universidade de Brasília, Brasília.

## See Also

[GermSpeed](#), [TimsonsIndex](#), [GermRateGeorge](#)

## Examples

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)

# From partial germination counts
#-----
EmergenceRateIndex(germ.counts = x, intervals = int)
EmergenceRateIndex(germ.counts = x, intervals = int,
  method = "melville")
EmergenceRateIndex(germ.counts = x, intervals = int,
  method = "melvillessantanaranal")
EmergenceRateIndex(germ.counts = x, intervals = int,
  method = "bilbrowanjura")
EmergenceRateIndex(germ.counts = x, intervals = int,
  total.seeds = 50, method = "fakorede")

# From cumulative germination counts
#-----
EmergenceRateIndex(germ.counts = y, intervals = int, partial = FALSE,)
EmergenceRateIndex(germ.counts = y, intervals = int, partial = FALSE,
  method = "melville")
EmergenceRateIndex(germ.counts = y, intervals = int, partial = FALSE,
  method = "melvillessantanaranal")
EmergenceRateIndex(germ.counts = y, intervals = int, partial = FALSE,
  method = "bilbrowanjura")
EmergenceRateIndex(germ.counts = y, intervals = int, partial = FALSE,
  total.seeds = 50, method = "fakorede")
```

---

FirstGermTime

*Time for first, last and peak germination*

---

## Description

Compute the following metrics:

**FirstGermTime** Time of first germination or Germination time lag ( $t_0$ ) (Edwards 1932; Czabator 1962; Goloff and Bazzaz 1975; Labouriau 1983; Ranal 1999; Quintanilla et al. 2000).

**LastGermTime** Time of last germination ( $t_g$ ) (Edwards 1932; Labouriau 1983; Ranal and de Santana 2006).

**TimeSpreadGerm** Time spread of germination (Al-Mudaris 1998; Kader 2005) or Germination distribution (Schrader and Graves 2000).

**PeakGermTime** Peak time of germination or Modal time of germination (Ranal and de Santana 2006).

## Usage

```
FirstGermTime(germ.counts, intervals, partial = TRUE)
```

```
LastGermTime(germ.counts, intervals, partial = TRUE)
```

```
PeakGermTime(germ.counts, intervals, partial = TRUE)
```

```
TimeSpreadGerm(germ.counts, intervals, partial = TRUE)
```

### Arguments

|             |   |
|-------------|---|
| germ.counts | Germination counts at each time interval. Can be partial or cumulative as specified in the argument partial.          |
| intervals   | The time intervals.   |
| partial     | logical. If TRUE, germ.counts is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE. |

### Details

Time of first germination indicates time of germination of the faster seeds in a seedlot.

Lower value of time of first germination indicates faster initiation of germination and lower value of time of last germination indicates faster termination of germination.

Time spread of germination ( $t_g - t_0$ ) indicates difference between faster and slower germinating members of a sample.

Peak time of germination is the time in which highest frequency of germinated seeds are observed. Multiple peak times of germination are possible and if detected are indicated by a warning message.

### Value

For FirstGermTime, the time of first germination value in the same unit of time as specified in the argument intervals.

For LastGermTime, the time of last germination value in the same unit of time as specified in the argument intervals.

For TimeSpreadGerm, the time spread of germination value in the same unit of time as specified in the argument intervals.

For PeakGermTime, the time(s) of peak germination value(s) as a numeric vector in the same unit of time as specified in the argument intervals.

### References

Al-Mudaris MA (1998). "Notes on various parameters recording the speed of seed germination." *Der Tropenlandwirt-Journal of Agriculture in the Tropics and Subtropics*, **99**(2), 147–154.

Czabator FJ (1962). "Germination value: An index combining speed and completeness of pine seed germination." *Forest Science*, **8**(4), 386–396.

Edwards TI (1932). "Temperature relations of seed germination." *The Quarterly Review of Biology*, **7**(4), 428–443.

Goloff AA, Bazzaz FA (1975). "A germination model for natural seed populations." *Journal of Theoretical Biology*, **52**(2), 259–283.

Kader MA (2005). "A comparison of seed germination calculation formulae and the associated interpretation of resulting data." *Journal and Proceedings of the Royal Society of New South Wales*, **138**, 65–75.

Labouriau LG (1983). *A Germinacao Das Sementes*. Organizacao dos Estados Americanos. Programa Regional de Desenvolvimento Cientifico e Tecnologico. Serie de Biologia. Monografia 24.

Quintanilla LG, Pajaron S, Pangua E, Amigo J (2000). “Effect of temperature on germination in northernmost populations of *Culcita macrocarpa* and *Woodwardia radicans*.” *Plant Biology*, **2**(6), 612–617.

Ranal MA (1999). “Effects of temperature on spore germination in some fern species from semideciduous mesophytic forest.” *American Fern Journal*, **89**(2), 149.

Ranal MA, de Santana DG (2006). “How and why to measure the germination process?” *Brazilian Journal of Botany*, **29**(1), 1–11.

Schrader JA, Graves WR (2000). “Seed germination and seedling growth of *Alnus maritima* from its three disjunct populations.” *Journal of the American Society for Horticultural Science*, **125**(1), 128–134.

## Examples

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
z <- c(0, 0, 0, 0, 11, 11, 9, 7, 1, 0, 1, 0, 0, 0)
int <- 1:length(x)

# From partial germination counts
#-----
FirstGermTime(germ.counts = x, intervals = int)
LastGermTime(germ.counts = x, intervals = int)
TimeSpreadGerm(germ.counts = x, intervals = int)
PeakGermTime(germ.counts = x, intervals = int)
# For multiple peak germination times
PeakGermTime(germ.counts = z, intervals = int)

# From cumulative germination counts
#-----
FirstGermTime(germ.counts = y, intervals = int, partial = FALSE)
LastGermTime(germ.counts = y, intervals = int, partial = FALSE)
TimeSpreadGerm(germ.counts = y, intervals = int, partial = FALSE)
PeakGermTime(germ.counts = y, intervals = int, partial = FALSE)
# For multiple peak germination time
PeakGermTime(germ.counts = cumsum(z), intervals = int, partial = FALSE)
```

---

FourPHFfit

*Fit four-parameter hill function*

---

## Description

Fit a four-parameter hill function (El-Kassaby et al. 2008) to cumulative germination count data and compute the associated parameters.



**Usage**

```
FourPHFfit(
  germ.counts,
  intervals,
  total.seeds,
  partial = TRUE,
  fix.y0 = TRUE,
  fix.a = TRUE,
  tmax,
  xp = c(10, 60),
  umin = 10,
  umax = 90,
  tries = 3
)
```

**Arguments**

|                          |   |
|--------------------------|---|
| <code>germ.counts</code> | Germination counts at each time interval. Can be partial or cumulative as specified in the argument <code>partial</code> .                  |
| <code>intervals</code>   | The time intervals.   |
| <code>total.seeds</code> | Total number of seeds.  |
| <code>partial</code>     | logical. If TRUE, <code>germ.counts</code> is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE.          |
| <code>fix.y0</code>      | Force the intercept of the y axis through 0.  |
| <code>fix.a</code>       | Fix <code>a</code> as the actual maximum germination percentage at the end of the experiment.   |
| <code>tmax</code>        | The time up to which AUC is to be computed.   |
| <code>xp</code>          | Germination percentage value(s) for which the corresponding time is to be computed as a numeric vector. Default is <code>c(10, 60)</code> . |
| <code>umin</code>        | The minimum germination percentage value for computing uniformity. Default is 10. Seed Details.   |
| <code>umax</code>        | The maximum germination percentage value for computing uniformity. Default is 90. Seed Details.   |
| <code>tries</code>       | The number of tries to be attempted to fit the curve. Default is 3.   |

**Details**

The cumulative germination count data of a seed lot can be modelled to fit a four-parameter hill function defined as follows (El-Kassaby et al. 2008).

$$y = y_0 + \frac{ax^b}{c^b + x^b}$$

Where,  $y$  is the cumulative germination percentage at time  $x$ ,  $y_0$  is the intercept on the y axis,  $a$  is the asymptote, or maximum cumulative germination percentage, which is equivalent to germination capacity,  $b$  is a mathematical parameter controlling the shape and steepness of the germination curve (the larger the  $b$  parameter, the steeper the rise toward the asymptote  $a$ , and the shorter the time between germination onset and maximum germination), and  $c$  is the "half-maximal activation level" which represents the time required for 50% of viable seeds to germinate ( $c$  is equivalent to the germination speed).

Once this function is fitted to the curve, FourPHFfit computes the time to 50% germination of total seeds (`t50.total`) or viable seeds (`t50.Germinated`). Similarly the time at any percentage of germination (in terms of both total and viable seeds) as specified in argument `xp` can be computed.

The time at germination onset (*lag*) can be computed as follows.

$$lag = b \sqrt{\frac{-y_0 c^b}{a + y_0}}$$

The value  $D_{lag-50}$  is defined as the duration between the time at germination onset (*lag*) and that at 50% germination (*c*).

The time interval between the percentages of viable seeds specified in the arguments `umin` and `umax` to germinate is computed as uniformity ( $U_{t_{max}-t_{min}}$ ).

$$U_{t_{max}-t_{min}} = t_{max} - t_{min}$$

The partial derivative of the four-parameter hill function gives the instantaneous rate of germination (*s*) as follows.

$$s = \frac{\partial y}{\partial x} = \frac{abc^b x^{b-1}}{(c^b + x^b)^2}$$

From this function for instantaneous rate of germination, the time at maximum germination rate (*TMGR*) can be estimated as follows.

$$TMGR = b \sqrt{\frac{c^b(b-1)}{b+1}}$$

TMGR represents the point in time when the instantaneous rate of germination starts to decline.

The area under the curve (*AUC*) is obtained by integration of the fitted curve between time 0 and time specified in the argument '`tmax`'.

Integration of the fitted curve gives the value of mean germination time (*MGT*) and the skewness of the germination curve is computed as the ratio of *MGT* and the time for 50% of viable seeds to germinate ( $t_{50}$ ).

$$Skewness = \frac{MGT}{t_{50}}$$

If final germination percentage is less than 10%, a warning is given, as the results may not be informative.

## Value

A list with the following components:

|                         |   |
|-------------------------|---|
| <code>data</code>       | A data frame with the data used for computing the model   |
| <code>Parameters</code> | A data.frame of parameter estimates, standard errors and p value.   |
| <code>Fit</code>        | A one-row data frame with estimates of model fitness such as log likelihoods, Akaike Information Criterion, Bayesian Information Criterion, deviance and residual degrees of freedom. |

|                |   |
|----------------|---|
| a              | The asymptote or the maximum cumulative germination percentage.                             |
| b              | The mathematical parameter controlling the shape and steepness of the germination curve.    |
| c              | The half-maximal activation level   |
| y0             | The intercept on the y axis.  |
| lag            | Time at germination onset   |
| Dlag50         | duration between the time at germination onset (lag) and that at 50% germination.           |
| t50.total      | time required for 50% of total seeds to germinate.  |
| txp.total      | time required for x% (as specified in argument xp) of total seeds to germinate.             |
| t50.Germinated | time required for 50% of viable/germinated seeds to germinate.                              |
| txp.Germinated | time required for x% (as specified in argument xp) of viable/germinated seeds to germinate. |
| Uniformity     | Time interval between umin% and umax% of viable seeds to germinate.                         |
| TMGR           | Time at maximum germination rate.   |
| AUC            | The estimate of area under the curve.   |
| MGT            | Mean germination time   |
| Skewness       | Skewness of mean germination time   |
| msg            | The message from nls.lm   |
| isConv         | Logical value indicating whether convergence was achieved.                                  |

## References

El-Kassaby YA, Moss I, Kolotelo D, Stoehr M (2008). "Seed germination: Mathematical representation and parameters extraction." *Forest Science*, **54**(2), 220–227.

## Examples

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)
total.seeds = 50

# From partial germination counts
#-----
FourPHFfit(germ.counts = x, intervals = int, total.seeds = 50, tmax = 20)

# From cumulative germination counts
#-----
FourPHFfit(germ.counts = y, intervals = int, total.seeds = 50, tmax = 20,
partial = FALSE)
```

FourPHFfit.bulk

*Fit four-parameter hill function for multiple samples***Description**

Fit four-parameter hill function from a data frame of germination counts recorded at specific time intervals for multiple samples in batch.

**Usage**

```
FourPHFfit.bulk(
  data,
  total.seeds.col,
  counts.intervals.cols,
  intervals,
  partial = TRUE,
  fix.y0 = TRUE,
  fix.a = TRUE,
  tmax,
  xp = c(10, 60),
  umin = 10,
  umax = 90,
  tries = 3
)
```

**Arguments**

|                       |   |
|-----------------------|---|
| data                  | A data frame with the germination count data. It should possess columns with <ul style="list-style-type: none"> <li>• Partial or cumulative germination counts per time interval (to be indicated by the argument counts.intervals.cols and</li> <li>• Total number of seeds tested (to be indicated by the argument total.seeds.col).</li> </ul> |
| total.seeds.col       | The name of the column in data with the total number of seeds tested.   |
| counts.intervals.cols | The names of columns in data with the germination counts (partial or cumulative, as indicated by the argument partial) per time interval (indicated by the argument intervals).   |
| intervals             | The time intervals.   |
| partial               | logical. If TRUE, germ.counts is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE.   |
| fix.y0                | Force the intercept of the y axis through 0.  |
| fix.a                 | Fix a as the actual maximum germination percentage at the end of the experiment.  |
| tmax                  | The time up to which AUC is to be computed.   |
| xp                    | Germination percentage value(s) for which the corresponding time is to be computed as a numeric vector. Default is c(10, 60).   |
| umin                  | The minimum germination percentage value for computing uniformity. Default is 10. Seed Details.   |

|                    |   |
|--------------------|---|
| <code>umax</code>  | The maximum germination percentage value for computing uniformity. Default is 90. Seed Details. |
| <code>tries</code> | The number of tries to be attempted to fit the curve. Default is 3.                             |

### Value

A data frame with the original data along with the various parameters of the respective fitted four-parameter hill function.

### References

El-Kassaby YA, Moss I, Kolotelo D, Stoehr M (2008). "Seed germination: Mathematical representation and parameters extraction." *Forest Science*, **54**(2), 220–227.

### See Also

This function is a wrapper around the [FourPHFfit](#) function for fitting four-parameter hill curve.

### Examples

```
data(gcdata)

counts.per.intervals <- c("Day01", "Day02", "Day03", "Day04", "Day05",
                          "Day06", "Day07", "Day08", "Day09", "Day10",
                          "Day11", "Day12", "Day13", "Day14")

FourPHFfit.bulk(gcdata, total.seeds.col = "Total Seeds",
                counts.intervals.cols = counts.per.intervals,
                intervals = 1:14, partial = TRUE,
                fix.y0 = TRUE, fix.a = TRUE, xp = c(10, 60),
                tmax = 20, tries = 3, umax = 90, umin = 10)
```

---

|                     |                               |
|---------------------|-------------------------------|
| <code>gcdata</code> | <i>Germination count data</i> |
|---------------------|-------------------------------|

---

### Description

An example germination count dataset. It includes germination count data over 14 days from five genotypes (G1 to G5) in three replications

### Usage

```
gcdata
```

### Format

A data frame with 17 columns:

**Genotype** The genotype.

**Rep** Replication.

**Day01** Number of seeds that germinated (germination counts) on Day 1.

**Day02** Number of seeds that germinated (germination counts) on Day 2.  
**Day03** Number of seeds that germinated (germination counts) on Day 3.  
**Day04** Number of seeds that germinated (germination counts) on Day 4.  
**Day05** Number of seeds that germinated (germination counts) on Day 5.  
**Day06** Number of seeds that germinated (germination counts) on Day 6.  
**Day07** Number of seeds that germinated (germination counts) on Day 7.  
**Day08** Number of seeds that germinated (germination counts) on Day 8.  
**Day09** Number of seeds that germinated (germination counts) on Day 9.  
**Day10** Number of seeds that germinated (germination counts) on Day 10.  
**Day11** Number of seeds that germinated (germination counts) on Day 11.  
**Day12** Number of seeds that germinated (germination counts) on Day 12.  
**Day13** Number of seeds that germinated (germination counts) on Day 13.  
**Day14** Number of seeds that germinated (germination counts) on Day 14.  
**Total Seeds** Total number of seeds tested.

### Examples

```
data(gcdata)
library(ggplot2)
library(reshape2)

# Plot partial germination counts over time
#-----
# Convert wide-from to long-form
gcdata_melt <- melt(gcdata[, !names(gcdata) %in% c("Total Seeds")],
  id.vars = c("Genotype", "Rep"))

ggplot(gcdata_melt, aes(x = variable, y = value,
  group = interaction(Genotype, Rep),
  colour = Genotype)) +
  geom_point(alpha = 0.7) +
  geom_line(alpha = 0.7) +
  ylab("Germination count (Partial)") +
  xlab("Intervals") +
  theme_bw()

# Plot partial germination counts over time
#-----

# Convert wide-from to long-form
# Compute cumulative germination counts
gcdata2 <- gcdata
gcdata2[, !names(gcdata2) %in% c("Genotype", "Rep", "Total Seeds")] <-
  t(apply(gcdata2[, !names(gcdata2) %in% c("Genotype", "Rep", "Total Seeds")], 1, cumsum))

gcdata_melt2 <- melt(gcdata2[, !names(gcdata2) %in% c("Total Seeds")],
  id.vars = c("Genotype", "Rep"))

ggplot(gcdata_melt2, aes(x = variable, y = value,
  group = interaction(Genotype, Rep),
  colour = Genotype)) +
```

```

geom_point(alpha = 0.7) +
geom_line(alpha = 0.7) +
ylab("Germination count (Cumulative)") +
xlab("Intervals") +
theme_bw()

# Compute germination indices
#-----

counts.per.intervals <- c("Day01", "Day02", "Day03", "Day04", "Day05",
                          "Day06", "Day07", "Day08", "Day09", "Day10",
                          "Day11", "Day12", "Day13", "Day14")
germination.indices(gcddata, total.seeds.col = "Total Seeds",
                   counts.intervals.cols = counts.per.intervals,
                   intervals = 1:14, partial = TRUE, max.int = 5)

```

---

|                     |                            |
|---------------------|----------------------------|
| germination.indices | <i>Germination Indices</i> |
|---------------------|----------------------------|

---

## Description

Compute germination indices from a data frame of germination counts recorded at specific time intervals for multiple samples in batch.

## Usage

```

germination.indices(
  data,
  total.seeds.col,
  counts.intervals.cols,
  intervals,
  partial = TRUE,
  FirstGermTime = TRUE,
  LastGermTime = TRUE,
  PeakGermTime = TRUE,
  TimeSpreadGerm = TRUE,
  t50 = TRUE,
  MeanGermTime = TRUE,
  VarGermTime = TRUE,
  SEGermTime = TRUE,
  CVGermTime = TRUE,
  MeanGermRate = TRUE,
  CVG = TRUE,
  VarGermRate = TRUE,
  SEGermRate = TRUE,
  GermRateRecip = TRUE,
  GermSpeed = TRUE,
  GermSpeedAccumulated = TRUE,
  GermSpeedCorrected = TRUE,
  WeightGermPercent = TRUE,
  MeanGermPercent = TRUE,

```

```

MeanGermNumber = TRUE,
TimsonsIndex = TRUE,
GermRateGeorge = TRUE,
max.int,
GermIndex = TRUE,
EmergenceRateIndex = TRUE,
PeakValue = TRUE,
GermValue = TRUE,
gv.k = 10,
CUGerm = TRUE,
GermSynchrony = TRUE,
GermUncertainty = TRUE
)

```

## Arguments

|                       |   |
|-----------------------|---|
| data                  | A data frame with the germination count data. It should possess columns with <ul style="list-style-type: none"> <li>• Partial or cumulative germination counts per time interval (to be indicated by the argument counts.intervals.cols and</li> <li>• Total number of seeds tested (to be indicated by the argument total.seeds.col).</li> </ul> |
| total.seeds.col       | The name of the column in data with the total number of seeds tested.   |
| counts.intervals.cols | The names of columns in data with the germination counts (partial or cumulative, as indicated by the argument partial) per time interval (indicated by the argument intervals).   |
| intervals             | The time intervals at which germination counts (in the columns specified in argument counts.intervals.cols) were recorded.  |
| partial               | logical. If TRUE, germination counts in counts.intervals.cols is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE.   |
| FirstGermTime         | logical. If TRUE, the Time of first germination or Germination time lag ( $t_0$ ) (Edwards 1932; Czabator 1962; Goloff and Bazzaz 1975; Labouriau 1983; Ranal 1999; Quintanilla et al. 2000) is computed. Default is TRUE.  |
| LastGermTime          | logical. If TRUE, the Time of last germination ( $t_g$ ) (Edwards 1932; Labouriau 1983; Ranal and de Santana 2006). is computed. Default is TRUE.   |
| PeakGermTime          | logical. If TRUE, the Peak time of germination or Modal time of germination (Ranal and de Santana 2006) is computed. Default is TRUE.   |
| TimeSpreadGerm        | logical. If TRUE, the Time spread of germination (Al-Mudaris 1998; Kader 2005) or Germination distribution (Schrader and Graves 2000). is computed. Default is TRUE.  |
| t50                   | logical. If TRUE, the Median germination time ( $t_{50}$ ) (Coolbear et al. 1984; Farooq et al. 2005) is computed. Default is TRUE.   |
| MeanGermTime          | logical. If TRUE, the Mean germination time ( $\bar{T}$ ) or Mean length of incubation time (Edmond and Drapala 1958; Czabator 1962; Ellis and Roberts 1980; Labouriau 1983; Ranal and de Santana 2006). or Sprouting index ( $SI$ ) (Smith and Millet 1964) or Germination Resistance ( $GR$ ) Gordon (1969, 1971) is computed. Default is TRUE. |
| VarGermTime           | logical. If TRUE, the Variance of germination time ( $s_T^2$ ) (Labouriau 1983; Ranal and de Santana 2006) is computed. Default is TRUE.  |



|                      |  |
|----------------------|--|
| SEGermTime           | logical. If TRUE, the Standard error of germination time ( $s_{\overline{T}}$ ) (Labouriau 1983; Ranal and de Santana 2006). is computed. Default is TRUE.   |
| CVGermTime           | logical. If TRUE, the Coefficient of variation of the germination time ( $CV_T$ ) (Ranal and de Santana 2006) is computed. Default is TRUE.  |
| MeanGermRate         | logical. If TRUE, the Mean germination rate ( $\overline{V}$ ) (Labouriau and Valadares 1976; Labouriau 1983; Ranal and de Santana 2006). is computed. Default is TRUE.  |
| CVG                  | logical. If TRUE, the Coefficient of velocity/rate of germination or Kotowski's coefficient of velocity ( $CVG$ ) (Kotowski 1926; Nichols and Heydecker 1968; Labouriau 1983; Scott et al. 1984; Bewley and Black 1994). is computed. Default is TRUE.   |
| VarGermRate          | logical. If TRUE, the Variance of germination rate ( $s_V^2$ ) (Labouriau 1983; Ranal and de Santana 2006) is computed. Default is TRUE.   |
| SEGermRate           | logical. If TRUE, the Standard error of germination rate ( $s_{\overline{V}}$ ) (Labouriau 1983; Ranal and de Santana 2006) is computed. Default is TRUE.  |
| GermRateRecip        | logical. If TRUE, the Germination rate as reciprocal of median time ( $v_{50}$ ) (Went 1957; Labouriau 1983; Ranal and de Santana 2006) is computed.   |
| GermSpeed            | logical. If TRUE, the Speed of germination or Germination rate index or Index of velocity of germination or Germination index or Emergence rate index (Throneberry and Smith 1955; Maguire 1962; Allan et al. 1962; Kendrick and Frankland 1969; Bouton et al. 1976; AOSA 1983; Khandakar and Bradbeer 1983; Bradbeer 1988; Wardle et al. 1991) considering both counts and percentages is computed. |
| GermSpeedAccumulated | logical. If TRUE, the Speed of accumulated germination (Bradbeer 1988; Wardle et al. 1991; Haugland and Brandsaeter 1996; de Santana and Ranal 2004) considering both counts and percentages is computed.  |
| GermSpeedCorrected   | logical. If TRUE, the Corrected speed of germination or Corrected germination rate index and the Corrected speed of accumulated germination (Evetts and Burnside 1972) is computed.  |
| WeightGermPercent    | logical. If TRUE, the Weighted germination percentage $WGP$ or Weighted germination index $WGI$ (Reddy 1978; Reddy et al. 1985) is computed.   |
| MeanGermPercent      | logical. If TRUE, the Mean/average germination percentage per unit time ( $\overline{GP}$ ) (Czabator 1962) is computed.   |
| MeanGermNumber       | logical. If TRUE, the Number of seeds germinated per unit time ( $\overline{N}$ ) (Khamassi et al. 2013) is computed.  |
| TimsonsIndex         | logical. If TRUE, the Timson's index or Timson's germination velocity index (Grose and Zimmer 1958; Timson 1965; Brown and Mayer 1988; Baskin and Baskin 1998) and it's modifications by Labouriau (Ranal and de Santana 2006) and (Khan and Ungar 1984) is computed.  |
| GermRateGeorge       | logical. If TRUE, the George's index George (1961) is computed.  |
| max.int              | The maximum interval value up to which Timson's index/George's germination rate is to be computed.   |
| GermIndex            | logical. If TRUE, the Germination index according to Melville et al. (1980) and its modification by de Santana and Ranal (2004) (Ranal and de Santana 2006) are computed.  |

## EmergenceRateIndex

logical. If TRUE, the Emergence rate index or Germination rate index are computed according to

- Shmueli and Goldberg (1971) and it's modification by de Santana and Ranal (2004) (Ranal and de Santana 2006);
- Bilbro and Wanjura (1982); and
- Fakorede and Ayoola (1980), Fakorede and Ojo (1981), and Fakorede and Agbana (1983).

PeakValue logical. If TRUE, the Peak value (*PV*) or Emergence Energy (*EE*) (Czabator 1962; Bonner 1967) is computed.

GermValue logical. If TRUE, the Germination value (Czabator 1962; Djavanshir and Pourbeik 1976) and its modification considering duration from start of test instead of from onset of germination (Brown and Mayer 1988) is computed.

gv.k The k Constant for computation of germination value. Default is 10.

CUGerm logical. If TRUE, the Coefficient of uniformity of germination (CUG) (Heydecker 1972; Bewley and Black 1994) is computed.

GermSynchrony logical. If TRUE, the Synchrony of germination (*Z* index) (Primack 1985; Ranal and de Santana 2006) is computed.

## GermUncertainty

logical. If TRUE, the Synchronization index ( $\bar{E}$ ) or Uncertainty of the germination process (*U*) or Informational entropy (*H*) (Shannon 1948; Labouriau and Valadares 1976; Labouriau 1983) is computed.

**Value**

A data frame with the original data along with the various single-value germination indices specified in the function arguments.

**References**

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See Also

This function is a wrapper around the different functions for computation of single-value germination indices in [germinationmetrics](#) ([FirstGermTime](#), [LastGermTime](#), [PeakGermTime](#), [TimeSpreadGerm](#), [t50](#), [MeanGermTime](#), [VarGermTime](#), [SEGermTime](#), [CVGermTime](#), [MeanGermRate](#), [CVG](#), [VarGermRate](#), [SEGermRate](#), [GermRateRecip](#), [GermSpeed](#), [GermSpeedAccumulated](#), [GermSpeedCorrected](#), [WeightGermPercent](#), [MeanGermPercent](#), [MeanGermPercent](#), [TimsonsIndex](#), [GermRateGeorge](#), [GermIndex](#), [EmergenceRateIndex](#), [GermValue](#), [PeakValue](#), [CUGerm](#), [GermSynchrony](#), [GermUncertainty](#))

Examples

```
data(gcdata)

counts.per.intervals <- c("Day01", "Day02", "Day03", "Day04", "Day05",
                          "Day06", "Day07", "Day08", "Day09", "Day10",
                          "Day11", "Day12", "Day13", "Day14")
germination.indices(gcdata, total.seeds.col = "Total Seeds",
                    counts.intervals.cols = counts.per.intervals,
                    intervals = 1:14, partial = TRUE, max.int = 5)
```

---

|           |                          |
|-----------|--------------------------|
| GermIndex | <i>Germination Index</i> |
|-----------|--------------------------|

---

Description

Compute the Germination index according to Melville et al. (1980) and its modification by de Santana and Ranal (2004) (Ranal and de Santana 2006).

Usage

```
GermIndex(
  germ.counts,
  intervals,
  partial = TRUE,
  total.seeds,
  modification = c("none", "santanaranal")
)
```

Arguments

|              |   |
|--------------|---|
| germ.counts  | Germination counts at each time interval. Can be partial or cumulative as specified in the argument partial.          |
| intervals    | The time intervals.   |
| partial      | logical. If TRUE, germ.counts is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE. |
| total.seeds  | Total number of seeds.  |
| modification | The modification to be applied. Either "none" or "santanaranal". Default is "none" (see <b>Details</b> ).             |

## Details

Germination index ( $GI$ ) is computed as follows (Melville et al. 1980).

$$GI = \sum_{i=1}^k \frac{|(T_k - T_i) N_i|}{N_t}$$

Where,  $T_i$  is the time from the start of the experiment to the  $i$ th interval (day for the example),  $N_i$  is the number of seeds germinated in the  $i$ th time interval (not the accumulated number, but the number corresponding to the  $i$ th interval),  $N_t$  is the total number of seeds used in the test, and  $k$  is the total number of time intervals.

A modified germination index ( $GI_{mod}$ ) was proposed by (de Santana and Ranal 2004) where total number of seeds tested ( $Nt$ ) is replaced by the total number of germinated seeds ( $N_g$ ) in the expression of Melville et al. (1980) to remove the effect of sample size (Ranal and de Santana 2006).

$$GI_{mod} = \sum_{i=1}^k \frac{|(T_k - T_i) N_i|}{N_g}$$

The term Germination index ( $GI$ ) has also been used to describe the mathematical expression for Speed of germination ([GermSpeed](#)) by AOSA (1983).

## Value

The value of the Germination index.

## References

AOSA (1983). *Seed Vigor Testing Handbook*. Association of Official Seed Analysts, Ithaca, NY, USA.

Melville AH, Galletta GJ, Draper AD, Ng TJ (1980). "Seed germination and early seedling vigor in progenies of inbred strawberry selections." *HortScience*, **15**(6, I), 749–750.

Ranal MA, de Santana DG (2006). "How and why to measure the germination process?" *Brazilian Journal of Botany*, **29**(1), 1–11.

de Santana DG, Ranal MA (2004). *Análise Da Germinação: Um Enfoque Estatístico*. Universidade de Brasília, Brasília.

## See Also

[GermSpeed](#)

## Examples

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)

# From partial germination counts
#-----
GermIndex(germ.counts = x, intervals = int, total.seeds = 50)
```

```
GermIndex(germ.counts = x, intervals = int, total.seeds = 50,
          modification = "none")
GermIndex(germ.counts = x, intervals = int, total.seeds = 50,
          modification = "santanaranal")

# From cumulative germination counts
#-----
GermIndex(germ.counts = y, intervals = int, partial = FALSE,
          total.seeds = 50)
GermIndex(germ.counts = y, intervals = int, partial = FALSE,
          total.seeds = 50,
          modification = "none")
GermIndex(germ.counts = y, intervals = int, partial = FALSE,
          total.seeds = 50,
          modification = "santanaranal")
```

---

|             |                               |
|-------------|-------------------------------|
| GermPercent | <i>Germination percentage</i> |
|-------------|-------------------------------|

---

**Description**

Compute the germination percentage or final germination percentage or germinability.

**Usage**

```
GermPercent(germinated.seeds, germ.counts, total.seeds, partial = TRUE)
```

**Arguments**

|                  |   |
|------------------|---|
| germinated.seeds | Number of germinated seeds  |
| germ.counts      | Germination counts at each time interval. Can be partial or cumulative as specified in the argument partial.          |
| total.seeds      | Total number of seeds.  |
| partial          | logical. If TRUE, germ.counts is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE. |

**Details**

Germination percentage is computed as follows (ISTA 2015).

$$GP = \frac{N_g}{N_t} \times 100$$

Where,  $N_g$  is the number of germinated seeds and  $N_t$  is the total number of seeds.  
The value of  $N_g$  can be either specified using the argument germinated.seeds or is computed from the germ.counts argument.

**Value**

The germination percentage (%) value.



## References

ISTA (2015). “Chapter 5: The germination test.” *International Rules for Seed Testing. International Seed Testing Association, Zurich, Switzerland.*, **2015**, i–5–56.

## Examples

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40)

# From partial germination counts
GermPercent(germ.counts = x, total.seeds = 50)

# From cumulative germination counts
GermPercent(germ.counts = y, total.seeds = 50, partial = FALSE)

# From number of germinated seeds
GermPercent(germinated.seeds = 40, total.seeds = 50)
```

---

|           |                             |
|-----------|-----------------------------|
| GermSpeed | <i>Speed of germination</i> |
|-----------|-----------------------------|

---

## Description

Compute the following metrics:

**GermSpeed** Speed of germination or Germination rate index or Index of velocity of germination or Germination index or Emergence rate index (Throneberry and Smith 1955; Maguire 1962; Allan et al. 1962; Kendrick and Frankland 1969; Bouton et al. 1976; Erbach 1982; AOSA 1983; Khandakar and Bradbeer 1983; Hsu and Nelson 1986; Bradbeer 1988; Wardle et al. 1991).

**GermSpeedAccumulated** Speed of accumulated germination (Bradbeer 1988; Wardle et al. 1991; Haugland and Brandsaeter 1996; de Santana and Ranal 2004).

**GermSpeedCorrected** Corrected speed of germination or Corrected germination rate index (Evetts and Burnside 1972).

## Usage

```
GermSpeed(
  germ.counts,
  intervals,
  partial = TRUE,
  percent = FALSE,
  total.seeds = NULL
)

GermSpeedAccumulated(
  germ.counts,
  intervals,
  partial = TRUE,
  percent = FALSE,
```

```

    total.seeds = NULL
  )

  GermSpeedCorrected(
    germ.counts,
    intervals,
    partial = TRUE,
    total.seeds,
    method = c("normal", "accumulated")
  )

```

### Arguments

|                          |  |
|--------------------------|--|
| <code>germ.counts</code> | Germination counts at each time interval. Can be partial or cumulative as specified in the argument <code>partial</code> .   |
| <code>intervals</code>   | The time intervals.  |
| <code>partial</code>     | logical. If TRUE, <code>germ.counts</code> is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE.   |
| <code>percent</code>     | logical. If TRUE, germination percentage is used instead of counts for computation. Default is FALSE.  |
| <code>total.seeds</code> | Total number of seeds. Mandatory for computation when <code>percent = TRUE</code> .  |
| <code>method</code>      | The method for computing germination speed in <code>GermSpeedCorrected</code> . Either "normal" ( <code>GermSpeed</code> ) or "accumulated" ( <code>GermSpeedAccumulated</code> ). |

### Details

`GermSpeed` computes the speed of germination according to the following formula (Throneberry and Smith 1955; Maguire 1962; Allan et al. 1962; Kendrick and Frankland 1969; Bouton et al. 1976; Erbach 1982; AOSA 1983; Khandakar and Bradbeer 1983; Hsu and Nelson 1986; Bradbeer 1988; Wardle et al. 1991).

$$S = \frac{N_1}{T_1} + \frac{N_2}{T_2} + \frac{N_3}{T_3} + \cdots + \frac{N_k}{T_k}$$

Where,  $N_1, N_2, N_3, \dots, N_k$  are the number of germinated seeds observed at time (days or hours)  $T_1, T_2, T_3, \dots, T_k$  after sowing (Not accumulated/cumulative number, but the number of seeds that germinated at the specific time) and  $k$  is the total number of time intervals.

It is the same as Emergence Rate Index (*ERI*) described by Allan et al. (1962), Erbach (1982) and Hsu and Nelson (1986) as well as Germination Index (*GI*) according to AOSA (1983).

The formula can also be described as follows.

$$S = \sum_{i=1}^k \frac{N_i}{T_i}$$

Where,  $T_i$  is the time from the start of the experiment to the  $i$ th interval,  $N_i$  is the number of seeds germinated in the  $i$ th time interval (not the accumulated number, but the number corresponding to the  $i$ th interval), and  $k$  is the total number of time intervals.

`GermSpeedAccumulated` computes the speed of accumulated germination as follows (Bradbeer 1988; Wardle et al. 1991; Haugland and Brandsaeter 1996; de Santana and Ranal 2004).

$$S_{accumulated} = \frac{N_1}{T_1} + \frac{N_1 + N_2}{T_2} + \frac{N_1 + N_2 + N_3}{T_3} + \dots + \frac{N_1 + N_2 + \dots + N_k}{T_k}$$

Where,  $N_1, N_2, N_3, \dots, N_k$  are the number of germinated seeds observed at time (days or hours)  $T_1, T_2, T_3, \dots, T_k$  after sowing (Not accumulated/cumulative number, but the number of seeds that germinated at the specific time), and  $k$  is the total number of time intervals.

The formula can also be described as follows.

$$S_{accumulated} = \sum_{i=1}^k \frac{\sum_{j=1}^i N_j}{T_i}$$

Where,  $T_i$  is the time from the start of the experiment to the  $i$ th interval,  $\sum_{j=1}^i N_j$  is the cumulative/accumulated number of seeds germinated in the  $i$ th time interval, and  $k$  is the total number of time intervals.

Speed of germination expresses the rate of germination in terms of the total number of seeds that germinate in a time interval. Higher values indicate greater and faster germination. This is useful for comparisons only when samples or treatments possess similar germinabilities. This is overcome by either using the corrected speed of germination or by using germination percentages instead of counts for computing speed.

GermSpeedCorrected computes the corrected speed of germination as follows (Evetts and Burnside 1972).

$$S_{corrected} = \frac{S}{FGP}$$

Where,  $FGP$  is the final germination percentage or germinability.

With percent = TRUE, germination percentage is used instead of counts for computation in GermSpeed and GermSpeedAccumulated.

## Value

For GermSpeed, the value of germination speed as % time<sup>-1</sup>.

For GermSpeedAccumulated, the value of accumulated germination speed as % time<sup>-1</sup>.

For GermSpeedCorrected, the corrected speed of germination.

## References

- AOSA (1983). *Seed Vigor Testing Handbook*. Association of Official Seed Analysts, Ithaca, NY, USA.
- Allan RE, Vogel OA, Peterson CJ (1962). "Seedling emergence rate of fall-sown wheat and its association with plant height and coleoptile length." *Agronomy Journal*, **54**(4), 347.
- Bouton JH, Dudeck AE, Smith RL (1976). "Germination in freshly harvested seed of centipede-grass." *Agronomy Journal*, **68**(6), 991.
- Bradbeer JW (1988). *Seed Dormancy and Germination*. Blackie, Glasgow and London.
- Erbach DC (1982). "Tillage for continuous corn and corn-soybean rotation." *Transactions of the*

ASAE, **25**(4), 906–0911.

Evetts LL, Burnside OC (1972). “Germination and seedling development of common milkweed and other species.” *Weed Science*, **20**(4), 371–378.

Haugland E, Brandsaeter LO (1996). “Experiments on bioassay sensitivity in the study of allelopathy.” *Journal of Chemical Ecology*, **22**(10), 1845–1859.

Hsu FH, Nelson CJ (1986). “Planting date effects on seedling development of perennial warm-season forage grasses. I. Field emergence.” *Agronomy Journal*, **78**(1), 33–38.

Kendrick RE, Frankland B (1969). “Photocontrol of germination in *Amaranthus caudatus*.” *Planta*, **85**(4), 326–339.

Khandakar AL, Bradbeer JW (1983). “Jute seed quality.” *Bangladesh Agricultural Research Council, Dhaka*.

Maguire JD (1962). “Speed of germination - Aid in selection and evaluation for seedling emergence and vigor.” *Crop Science*, **2**(2), 176–177.

Throneberry GO, Smith FG (1955). “Relation of respiratory and enzymatic activity to corn seed viability.” *Plant Physiology*, **30**(4), 337–343.

Wardle DA, Ahmed M, Nicholson KS (1991). “Allelopathic influence of nodding thistle (*Carduus nutans* L.) seeds on germination and radicle growth of pasture plants.” *New Zealand Journal of Agricultural Research*, **34**(2), 185–191.

de Santana DG, Ranal MA (2004). *Análise Da Germinação: Um Enfoque Estatístico*. Universidade de Brasília, Brasília.

## Examples

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)

# From partial germination counts
#-----
GermSpeed(germ.counts = x, intervals = int)
GermSpeedAccumulated(germ.counts = x, intervals = int)
GermSpeedCorrected(germ.counts = x, intervals = int, total.seeds = 50,
                    method = "normal")
GermSpeedCorrected(germ.counts = x, intervals = int, total.seeds = 50,
                    method = "accumulated")

# From partial germination counts (with percentages instead of counts)
#-----
GermSpeed(germ.counts = x, intervals = int,
           percent = TRUE, total.seeds = 50)
GermSpeedAccumulated(germ.counts = x, intervals = int,
                     percent = TRUE, total.seeds = 50)

# From cumulative germination counts
#-----
GermSpeed(germ.counts = y, intervals = int, partial = FALSE)
```

```

GermSpeedAccumulated(germ.counts = y, intervals = int, partial = FALSE)
GermSpeedCorrected(germ.counts = y, intervals = int,
                    partial = FALSE, total.seeds = 50, method = "normal")
GermSpeedCorrected(germ.counts = y, intervals = int,
                    partial = FALSE, total.seeds = 50, method = "accumulated")

# From cumulative germination counts (with percentages instead of counts)
#-----
GermSpeed(germ.counts = y, intervals = int, partial = FALSE,
           percent = TRUE, total.seeds = 50)
GermSpeedAccumulated(germ.counts = y, intervals = int, partial = FALSE,
                      percent = TRUE, total.seeds = 50)

```

GermSynchrony

*Synchrony and uncertainty of germination*

### Description

Compute the following metrics:

**GermSynchrony** Synchrony of germination ( $Z$  index) (Primack 1985; Ranal and de Santana 2006).

**GermUncertainty** Synchronization index ( $\bar{E}$ ) or Uncertainty of the germination process ( $U$ ) or Informational entropy ( $H$ ) (Shannon 1948; Labouriau and Valadares 1976; Labouriau 1983).

### Usage

```
GermSynchrony(germ.counts, intervals, partial = TRUE)
```

```
GermUncertainty(germ.counts, intervals, partial = TRUE)
```

### Arguments

|                    |  |
|--------------------|--|
| <b>germ.counts</b> | Germination counts at each time interval. Can be partial or cumulative as specified in the argument <b>partial</b> .         |
| <b>intervals</b>   | The time intervals.  |
| <b>partial</b>     | logical. If TRUE, <b>germ.counts</b> is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE. |

### Details

**GermSynchrony** computes the value of synchrony of germination ( $Z$  index) as follows (Primack 1985; Ranal and de Santana 2006).

$$Z = \frac{\sum_{i=1}^k C_{N_i,2}}{C_{\Sigma N_i,2}}$$

Where,  $C_{N_i,2}$  is the partial combination of the two germinated seeds from among  $N_i$ , the number of seeds germinated on the  $i$ th time interval (estimated as  $C_{N_i,2} = \frac{N_i(N_i-1)}{2}$ ), and  $C_{\Sigma N_i,2}$  is the partial combination of the two germinated seeds from among the total number of seeds germinated at the final count, assuming that all seeds that germinated did so simultaneously.

GermUncertainty computes the value of synchronization index ( $\overline{E}$ ) or uncertainty of the germination process ( $U$ ) or informational entropy ( $H$ ) as follows (Shannon 1948; Labouriau and Valadares 1976; Labouriau 1983).

$$\overline{E} = - \sum_{i=1}^k f_i \log_2 f_i$$

Where,  $f_i$  is the relative frequency of germination (estimated as  $f_i = \frac{N_i}{\sum_{i=1}^k N_i}$ ),  $N_i$  is the number of seeds germinated on the  $i$ th time interval, and  $k$  is the total number of time intervals.

### Value

For GermUncertainty, the value of uncertainty of germination process.

For GermSynchrony, the value of synchrony of germination.

### References

- Labouriau LG (1983). “Uma nova linha de pesquisa na fisiologia da germinacao das sementes.” *Anais do XXXIV Congresso Nacional de Botanica. SBB, Porto Alegre*, 11–50.
- Labouriau LG, Valadares MEB (1976). “On the germination of seeds of *Calotropis procera* (Ait.) Ait. f.” *Anais da Academia Brasileira de Ciencias*, **48**(263-284).
- Primack RB (1985). “Longevity of individual flowers.” *Annual Review of Ecology and Systematics*, **16**(1), 15–37.
- Ranal MA, de Santana DG (2006). “How and why to measure the germination process?” *Brazilian Journal of Botany*, **29**(1), 1–11.
- Shannon CE (1948). “A mathematical theory of communication.” *Bell System Technical Journal*, **27**(3), 379–423.

### See Also

[CUGerm](#)

### Examples

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)

# From partial germination counts
#-----
GermSynchrony(germ.counts = x, intervals = int)
GermUncertainty(germ.counts = x, intervals = int)

# From cumulative germination counts
#-----
GermSynchrony(germ.counts = y, intervals = int, partial = FALSE)
GermUncertainty(germ.counts = y, intervals = int, partial = FALSE)
```

GermValue

*Peak value and germination value***Description**

Compute the Peak value (*PV*) or Emergence Energy (*EE*) (Czabator 1962; Bonner 1967) and Germination value (*GV*) (Czabator 1962; Djavanshir and Pourbeik 1976; Brown and Mayer 1988).

**Usage**

```
PeakValue(germ.counts, intervals, total.seeds, partial = TRUE)
```

```
GermValue(
  germ.counts,
  intervals,
  total.seeds,
  partial = TRUE,
  method = c("czabator", "dp"),
  from.onset = TRUE,
  k = 10
)
```

**Arguments**

|             |  |
|-------------|--|
| germ.counts | Germination counts at each time interval. Can be partial or cumulative as specified in the argument <i>partial</i> .                                     |
| intervals   | The time intervals.  |
| total.seeds | Total number of seeds.   |
| partial     | logical. If TRUE, germ.counts is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE.                                    |
| method      | The method for computing germination value. Either "czabator" or "dp".   |
| from.onset  | logical. If TRUE, duration is considered only from the onset of germination. If FALSE, full duration of germination test is considered. Default is TRUE. |
| k           | Constant (See <b>Details</b> ). Default is 10.   |

**Details**

Peak value (*PV*) is the maximum quotient obtained by dividing successive cumulative germination values by the relevant incubation time (Czabator 1962).

$$PV = \max \left( \frac{G_1}{T_1}, \frac{G_2}{T_2}, \dots, \frac{G_k}{T_k} \right)$$

Where,  $T_i$  is the time from the start of the experiment to the  $i$ th interval,  $G_i$  is the cumulative germination percentage in the  $i$ th time interval, and  $k$  is the total number of time intervals.

It represents the mean daily germination of the most vigorous component of the seed lot, and is a mathematical expression of the break, or shoulder, of a typical sigmoid germination curve (Djavanshir and Pourbeik 1976). It is the accumulated number of seeds germinated at the point on

the germination curve at which the rate of germination starts to decrease. It is also described as Emergence energy (Bonner 1967).

For daily germination counts, germination value ( $GV$ ) is computed as follows (Czabator 1962).

$$GV = PV \times MDG$$

Where,  $PV$  is the peak value, and  $MDG$  is the mean daily germination percentage from the onset of germination.

Germination value ( $GV$ ) can also be computed for other time intervals of successive germination counts, by replacing  $MDG$  with the mean germination percentage per unit time ( $\overline{GP}$ ).

A new estimation of germination value was given by Djavanshir and Pourbeik (1976) as follows.

$$GV = \frac{\sum DGS}{N} \times GP \times c$$

Where,  $DGS$  is the daily germination speed computed by dividing cumulative germination percentage by the number of days since the onset of germination,  $N$  is the frequency or number of DGS calculated during the test,  $GP$  is the germination percentage expressed over 100, and  $c$  is a constant. The value of  $c$  is decided on the basis of average daily speed of germination ( $\frac{\sum DGS}{N}$ ). If it is less than 10, then  $c$  value of 10 can be used and if it is more than 10, then value of 7 or 8 can be used for  $c$ .

For both methods of computing  $GV$ , only the duration from the onset of germination is considered by default. Alternatively, modified  $GV$  ( $GV_{mod}$ ), where the entire duration from the beginning of the test is considered can be obtained by using the argument `from.onset = FALSE` (Brown and Mayer 1988).

## Value

A list with the following components:

Germination Value

The germination value

Calculations

The data frame of calculations.

testend

The end of test value (Only for method dp).

## References

- Bonner FT (1967). "Ideal sowing depth for sweetgum seed." *Tree Planters' Notes*, **18**(1), 1–1.
- Brown RF, Mayer DG (1988). "Representing cumulative germination. 1. A critical analysis of single-value germination indices." *Annals of Botany*, **61**(2), 117–125.
- Czabator FJ (1962). "Germination value: An index combining speed and completeness of pine seed germination." *Forest Science*, **8**(4), 386–396.
- Djavanshir K, Pourbeik H (1976). "Germination value-A new formula." *Silvae genetica*, **25**(2), 79–83.



**Examples**

```

x <- c(0, 0, 34, 40, 21, 10, 4, 5, 3, 5, 8, 7, 7, 6, 6, 4, 0, 2, 0, 2)
y <- c(0, 0, 34, 74, 95, 105, 109, 114, 117, 122, 130, 137, 144, 150,
      156, 160, 160, 162, 162, 164)
int <- 1:length(x)
total.seeds = 200

# From partial germination counts
#-----
PeakValue(germ.counts = x, intervals = int, total.seeds = 200)
GermValue(germ.counts = x, intervals = int, total.seeds = 200,
          method = "czabator")
GermValue(germ.counts = x, intervals = int, total.seeds = 200,
          method = "dp", k = 10)
GermValue(germ.counts = x, intervals = int, total.seeds = 200,
          method = "czabator", from.onset = FALSE)
GermValue(germ.counts = x, intervals = int, total.seeds = 200,
          method = "dp", k = 10, from.onset = FALSE)

# From cumulative germination counts
#-----
PeakValue(germ.counts = y, interval = int, total.seeds = 200,
          partial = FALSE)
GermValue(germ.counts = y, intervals = int, total.seeds = 200,
          partial = FALSE, method = "czabator")
GermValue(germ.counts = y, intervals = int, total.seeds = 200,
          partial = FALSE, method = "dp", k = 10)
GermValue(germ.counts = y, intervals = int, total.seeds = 200,
          partial = FALSE, method = "czabator", from.onset = FALSE)
GermValue(germ.counts = y, intervals = int, total.seeds = 200,
          partial = FALSE, method = "dp", k = 10, from.onset = FALSE)

```

MeanGermPercent

*Mean germination percentage and number of seeds per time interval***Description**

Compute the following metrics:

MeanGermPercent Mean/average germination percentage per unit time ( $\overline{GP}$ ) (Czabator 1962).

MeanGermNumber Number of seeds germinated per unit time ( $\overline{N}$ ) (Khamassi et al. 2013).

**Usage**

```

MeanGermPercent(
  germinated.seeds,
  germ.counts,
  total.seeds,
  intervals,
  partial = TRUE
)

MeanGermNumber(germ.counts, intervals, partial = TRUE)

```

**Arguments**

|                  |  |
|------------------|--|
| germinated.seeds | Number of germinated seeds   |
| germ.counts      | Germination counts at each time interval. Can be partial or cumulative as specified in the argument <code>partial</code> .         |
| total.seeds      | Total number of seeds.   |
| intervals        | The time intervals.  |
| partial          | logical. If TRUE, <code>germ.counts</code> is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE. |

**Details**

Mean germination percentage per unit time ( $\overline{GP}$ ) is computed as follows (Czabator 1962).

$$\overline{GP} = \frac{GP}{T_k}$$

Where,  $GP$  is the final germination percentage,  $T_k$  is the time at the  $k$ th time interval, and  $k$  is the total number of time intervals required for final germination.

Mean number of seeds germinated per unit time ( $\overline{N}$ ) is computed as follows (Khamassi et al. 2013).

$$\overline{N} = \frac{N_g}{T_k}$$

Where,  $N_g$  is the number of germinated seeds at the end of the germination test,  $T_k$  is the time at the  $k$ th time interval, and  $k$  is the total number of time intervals required for final germination.

**Value**

The value of mean germination percentage or mean number of seeds per time interval.

**References**

Czabator FJ (1962). "Germination value: An index combining speed and completeness of pine seed germination." *Forest Science*, **8**(4), 386–396.

Khamassi K, Harbaoui K, Jaime ATdS, Jeddi FB (2013). "Optimal germination temperature assessed by indices and models in field bean (*Vicia faba* L. var. *minor*).*" Agriculturae Conspectus Scientificus*, **78**(2), 131–136.

**See Also**

[GermPercent](#)

**Examples**

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)

# From partial germination counts
#-----
```

```

MeanGermPercent(germ.counts = x, total.seeds = 50, intervals = int)
MeanGermNumber(germ.counts = x, intervals = int)

# From cumulative germination counts
#-----
MeanGermPercent(germ.counts = y, total.seeds = 50, intervals = int, partial = FALSE)
MeanGermNumber(germ.counts = y, intervals = int, partial = FALSE)

# From number of germinated seeds
#-----
MeanGermPercent(germinated.seeds = 40, total.seeds = 50, intervals = int)

```

---

|              |                         |
|--------------|-------------------------|
| MeanGermRate | <i>Germination rate</i> |
|--------------|-------------------------|

---

## Description

Compute the following metrics:

**MeanGermRate** Mean germination rate ( $\bar{V}$ ) (Labouriau and Valadares 1976; Labouriau 1983; Ranal and de Santana 2006).

**VarGermRate** Variance of germination rate ( $s_V^2$ ) (Labouriau 1983; Ranal and de Santana 2006).

**SEGermRate** Standard error of germination rate ( $s_{\bar{V}}$ ) (Labouriau 1983; Ranal and de Santana 2006).

**CVG** Coefficient of velocity/rate of germination or Kotowski's coefficient of velocity (*CVG*) (Kotowski 1926; Nichols and Heydecker 1968; Labouriau 1983; Scott et al. 1984; Bewley and Black 1994).

**GermRateRecip** Germination rate as reciprocal of median time ( $v_{50}$ ) (Went 1957; Labouriau 1983; Ranal and de Santana 2006).

## Usage

```
MeanGermRate(germ.counts, intervals, partial = TRUE)
```

```
CVG(germ.counts, intervals, partial = TRUE)
```

```
VarGermRate(germ.counts, intervals, partial = TRUE)
```

```
SEGermRate(germ.counts, intervals, partial = TRUE)
```

```

GermRateRecip(
  germ.counts,
  intervals,
  partial = TRUE,
  method = c("coolbear", "farooq")
)

```

### Arguments

|             |   |
|-------------|---|
| germ.counts | Germination counts at each time interval. Can be partial or cumulative as specified in the argument partial.          |
| intervals   | The time intervals.   |
| partial     | logical. If TRUE, germ.counts is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE. |
| method      | The method for computing median germination time. Either "coolbear" or "farooq".                                      |

### Details

MeanGermRate computes the mean germination rate ( $\bar{V}$ ) according to the following formula (Labouriau and Valadares 1976; Labouriau 1983; Ranal and de Santana 2006).

$$\bar{V} = \frac{\sum_{i=1}^k N_i}{\sum_{i=1}^k N_i T_i}$$

Where,  $T_i$  is the time from the start of the experiment to the  $i$ th interval,  $N_i$  is the number of seeds germinated in the  $i$ th time interval (not the accumulated number, but the number corresponding to the  $i$ th interval), and  $k$  is the total number of time intervals.

It is the inverse of mean germination time ( $\bar{T}$ ).

$$\bar{V} = \frac{1}{\bar{T}}$$

VarGermRate computes the variance of germination rate ( $s_V^2$ ) according to the following formula (Labouriau 1983; Ranal and de Santana 2006).

$$s_V^2 = \bar{V}^4 \times s_T^2$$

Where,  $s_T^2$  is the variance of germination time.

SEGermRate computes the standard error of germination time ( $s_{\bar{V}}$ ) according to the following formula (Labouriau 1983; Ranal and de Santana 2006).

$$s_{\bar{V}} = \sqrt{\frac{s_V^2}{\sum_{i=1}^k N_i}}$$

Where,  $N_i$  is the number of seeds germinated in the  $i$ th time interval (not the accumulated number, but the number corresponding to the  $i$ th interval), and  $k$  is the total number of time intervals.

CVG computes the coefficient of velocity/rate of germination or Kotowski's coefficient of velocity ( $CVG$ ) according to the following formula (Kotowski 1926; Nichols and Heydecker 1968; Labouriau 1983; Scott et al. 1984; Bewley and Black 1994).

$$CVG = \frac{\sum_{i=1}^k N_i}{\sum_{i=1}^k N_i T_i} \times 100$$

$$CVG = \bar{V} \times 100$$

Where,  $T_i$  is the time from the start of the experiment to the  $i$ th interval,  $N_i$  is the number of seeds germinated in the  $i$ th time interval (not the accumulated number, but the number corresponding to the  $i$ th interval), and  $k$  is the total number of time intervals.

GermRateRecip computes the germination rate ( $v_{50}$ ) as the reciprocal of the median germination time ( $t_{50}$ ) (Went 1957; Labouriau 1983; Ranal and de Santana 2006) computed according to the methods of Coolbear et al. (1984) or Farooq et al. (2005) as follows.

$$v_{50} = \frac{1}{t_{50}}$$

## Value

For MeanGermRate, the mean germination rate value as  $\text{time}^{-1}$ .

For VarGermTime, the variance of germination rate value as  $\text{time}^{-2}$ .

For SEGermTime, the standard error of germination rate as  $\text{time}^{-1}$ .

For CVG, the value of Coefficient of of velocity/rate of germination or Kotowski's coefficient of velocity.

For GermRateRecip, the value of germination rate as  $\text{time}^{-1}$ .

## References

- Bewley JD, Black M (1994). *Seeds: Physiology of Development and Germination..* Plenum Publishing Corporation, New York, USA. ISBN 0-306-44748-7.
- Coolbear P, Francis A, Grierson D (1984). "The effect of low temperature pre-sowing treatment on the germination performance and membrane integrity of artificially aged tomato seeds." *Journal of Experimental Botany*, **35**(11), 1609–1617.
- Farooq M, Basra SMA, Ahmad N, Hafeez K (2005). "Thermal hardening: A new seed vigor enhancement tool in rice." *Journal of Integrative Plant Biology*, **47**(2), 187–193.
- Kotowski F (1926). "Temperature relations to germination of vegetable seeds." *Proceedings of the American Society for Horticultural Science*, **23**, 176–184.
- Labouriau LG (1983). "Uma nova linha de pesquisa na fisiologia da germinacao das sementes." *Anais do XXXIV Congresso Nacional de Botanica. SBB, Porto Alegre*, 11–50.
- Labouriau LG, Valadares MEB (1976). "On the germination of seeds of *Calotropis procera* (Ait.) Ait. f." *Anais da Academia Brasileira de Ciencias*, **48**(263-284).
- Nichols MA, Heydecker W (1968). "Two approaches to the study of germination data." *Proceedings of the International Seed Testing Association*, **33**(3), 531–540.
- Ranal MA, de Santana DG (2006). "How and why to measure the germination process?" *Brazilian Journal of Botany*, **29**(1), 1–11.
- Scott SJ, Jones RA, Williams WA (1984). "Review of data analysis methods for seed germination." *Crop Science*, **24**(6), 1192–1199.
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**See Also**

[MeanGermTime](#), [t50](#)

**Examples**

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)

# From partial germination counts
#-----
MeanGermRate(germ.counts = x, intervals = int)
CVG(germ.counts = x, intervals = int)
VarGermRate(germ.counts = x, intervals = int)
SEGermRate(germ.counts = x, intervals = int)
GermRateRecip(germ.counts = x, intervals = int, method = "coolbear")
GermRateRecip(germ.counts = x, intervals = int, method = "farooq")

# From cumulative germination counts
#-----
MeanGermRate(germ.counts = y, intervals = int, partial = FALSE)
CVG(germ.counts = y, intervals = int, partial = FALSE)
VarGermRate(germ.counts = y, intervals = int, partial = FALSE)
SEGermRate(germ.counts = y, intervals = int, partial = FALSE)
GermRateRecip(germ.counts = y, intervals = int,
               method = "coolbear", partial = FALSE)
GermRateRecip(germ.counts = y, intervals = int,
               method = "farooq", partial = FALSE)
```

---

MeanGermTime

*Germination time*

---

**Description**

Compute the following metrics:

**MeanGermTime** Mean germination time ( $\bar{T}$ ) or Mean length of incubation time (Edmond and Drapala 1958; Czabator 1962; Mock and Eberhart 1972; Ellis and Roberts 1980; Labouriau 1983; Ranal and de Santana 2006).

**VarGermTime** Variance of germination time ( $s_T^2$ ) (Labouriau 1983; Ranal and de Santana 2006).

**SEGermTime** Standard error of germination time ( $s_{\bar{T}}$ ) (Labouriau 1983; Ranal and de Santana 2006).

**CVGermTime** Coefficient of variation of the germination time ( $CV_T$ ) (Gomes 1960; Ranal and de Santana 2006).

**Usage**

```
MeanGermTime(germ.counts, intervals, partial = TRUE)
```

```
VarGermTime(germ.counts, intervals, partial = TRUE)
```

```
SEGermTime(germ.counts, intervals, partial = TRUE)
```

```
CVGermTime(germ.counts, intervals, partial = TRUE)
```

### Arguments

|             |   |
|-------------|---|
| germ.counts | Germination counts at each time interval. Can be partial or cumulative as specified in the argument partial.          |
| intervals   | The time intervals.   |
| partial     | logical. If TRUE, germ.counts is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE. |

### Details

MeanGermTime computes the mean germination time according to the following formula (Edmond and Drapala 1958; Czabator 1962; Smith and Millet 1964; Ellis and Roberts 1980; Labouriau 1983; Ranal and de Santana 2006).

$$\bar{T} = \frac{\sum_{i=1}^k N_i T_i}{\sum_{i=1}^k N_i}$$

Where,  $T_i$  is the time from the start of the experiment to the  $i$ th interval,  $N_i$  is the number of seeds germinated in the  $i$ th time interval (not the accumulated number, but the number corresponding to the  $i$ th interval), and  $k$  is the total number of time intervals.

It is the same as Sprouting Index (*SI*) or Emergence Index (*EI*) described by Smith and Millet (1964) and Mock and Eberhart (1972) as well as Germination Resistance (*GR*) described by Gordon (1969, 1971).

It is the inverse of mean germination rate ( $\bar{V}$ ).

$$\bar{T} = \frac{1}{\bar{V}}$$

It indicates the average length of time required for maximum germination of a seed lot. Lower the  $\bar{T}$ , faster the sample has germinated and reflects seed vigor.

VarGermTime computes the variance of germination time according to the following formula (Labouriau 1983; Ranal and de Santana 2006).

$$s_T^2 = \frac{\sum_{i=1}^k N_i (T_i - \bar{T})^2}{\sum_{i=1}^k N_i - 1}$$

Where,  $T_i$  is the time from the start of the experiment to the  $i$ th interval,  $N_i$  is the number of seeds germinated in the  $i$ th time interval (not the accumulated number, but the number corresponding to the  $i$ th interval), and  $k$  is the total number of time intervals.

SEGermTime computes the standard error of germination time ( $s_{\bar{T}}$ ) according to the following formula (Labouriau 1983; Ranal and de Santana 2006).

$$s_{\bar{T}} = \sqrt{\frac{s_T^2}{\sum_{i=1}^k N_i}}$$

Where,  $N_i$  is the number of seeds germinated in the  $i$ th time interval (not the accumulated number, but the number corresponding to the  $i$ th interval), and  $k$  is the total number of time intervals.

It signifies the accuracy of the calculation of the mean germination time.

CVGermTime computes the coefficient of variation of germination time ( $CV_T$ ) according to the following formula (Gomes 1960; Ranal and de Santana 2006).

$$CV_T = \frac{\sqrt{s_T^2}}{\bar{T}}$$

This indicates the uniformity of germination and permits comparisons irrespective of the magnitude of mean germination time ( $\bar{T}$ ).

## Value

For MeanGermTime, the mean germination time value in the same unit of time as specified in the argument intervals.

For VarGermTime, the variance of germination time value as time<sup>2</sup>.

For SEGermTime, the standard error of germination time in the same unit of time specified in the argument intervals.

For CVGermTime, the value of coefficient of variation of the germination time.

## References

- Czabator FJ (1962). "Germination value: An index combining speed and completeness of pine seed germination." *Forest Science*, **8**(4), 386–396.
- Edmond JB, Drapala WJ (1958). "The effects of temperature, sand and soil, and acetone on germination of okra seed." *Proceedings of the American Society for Horticultural Science*, **71**, 428–434.
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- Gordon AG (1969). "Some observations on the germination energy tests for cereals." *Proceedings of the Association of Official Seed Analysts*, **59**, 58–72.
- Gordon AG (1971). "The germination resistance test - A new test for measuring germination quality of cereals." *Canadian Journal of Plant Science*, **51**(2), 181–183.
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- Mock JJ, Eberhart SA (1972). "Cold tolerance in adapted maize populations." *Crop Science*, **12**(4), 466–469.
- Ranal MA, de Santana DG (2006). "How and why to measure the germination process?" *Brazilian Journal of Botany*, **29**(1), 1–11.
- Smith PG, Millet AH (1964). "Germinating and sprouting responses of the tomato at low temperatures." *Journal of the American Society for Horticultural Science*, **84**, 480–484.



**See Also**[MeanGermRate](#)**Examples**

```

x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)

# From partial germination counts
#-----
MeanGermTime(germ.counts = x, intervals = int)
VarGermTime(germ.counts = x, intervals = int)
SEGermTime(germ.counts = x, intervals = int)
CVGermTime(germ.counts = x, intervals = int)

# From cumulative germination counts
#-----
MeanGermTime(germ.counts = y, intervals = int, partial = FALSE)
VarGermTime(germ.counts = y, intervals = int, partial = FALSE)
SEGermTime(germ.counts = y, intervals = int, partial = FALSE)
CVGermTime(germ.counts = y, intervals = int, partial = FALSE)

```

plot.FourPHFfit

*Plot the four-parameter hill function fitted cumulative germination curve from a FourPHFfit object*

**Description**

plot.FourPHFfit plots the four-parameter hill function fitted cumulative germination curve (FPHF curve) from a FourPHFfit object as an object of class ggplot. Further, the rate of germination curve (RoG curve) is plotted and different parameters annotated as specified in the different arguments.

**Usage**

```

## S3 method for class 'FourPHFfit'
plot(
  x,
  rog = TRUE,
  t50.total = TRUE,
  t50.germ = TRUE,
  tmgr = TRUE,
  mgt = TRUE,
  uniformity = TRUE,
  limits = TRUE,
  plotlabels = TRUE,
  ...
)

```

**Arguments**

|            |   |
|------------|---|
| x          | An object of class <code>FourPHFfit</code> obtained as output from the <code>FourPHFfit</code> function.  |
| rog        | If TRUE, plots the Rate of Germination curve (RoG). Default is TRUE.  |
| t50.total  | If TRUE, highlights the time required for 50% of total seeds to germinate ( $t_{50_{\text{Germ}}}$ ) as a vertical line. Default is TRUE.   |
| t50.germ   | If TRUE, highlights the time required for 50% of viable/germinated seeds to germinate ( $t_{50_{\text{Total}}}$ ) as a vertical line. Default is TRUE.                                |
| tmgr       | If TRUE, highlights the Time at Maximum Germination Rate (TMGR) as a vertical line. Default is TRUE.  |
| mgt        | If TRUE, highlights the Mean Germination Time (MGT) as a vertical line. Default is TRUE.  |
| uniformity | If TRUE, highlights the uniformity value ( $U_{t_{\text{max}}-t_{\text{min}}}$ ) as a horizontal line. Default is TRUE.   |
| limits     | logical. If TRUE, set the limits of y axis (germination percentage) between 0 and 100 in the germination curve plot. If FALSE, limits are set according to the data. Default is TRUE. |
| plotlabels | logical. If TRUE, adds labels to the germination curve plot. Default is TRUE.   |
| ...        | Default plot arguments.   |

**Value**

The plot of the cumulative germination curve as an object of class `ggplot`.

**See Also**

[FourPHFfit](#)

**Examples**

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)
total.seeds = 50

# From partial germination counts
#-----
fit1 <- FourPHFfit(germ.counts = x, intervals = int,
                  total.seeds = 50, tmax = 20)

# From cumulative germination counts
#-----
fit2 <- FourPHFfit(germ.counts = y, intervals = int,
                  total.seeds = 50, tmax = 20, partial = FALSE)

# Default plots
plot(fit1)
plot(fit2)

# No labels
plot(fit1, plotlabels = FALSE)
```

```

plot(fit2, plotlabels = FALSE)

# Only the FPHF curve
plot(fit1, rog = FALSE, t50.total = FALSE, t50.germ = FALSE,
      tmgr = FALSE, mgt = FALSE, uniformity = FALSE)
plot(fit2, rog = FALSE, t50.total = FALSE, t50.germ = FALSE,
      tmgr = FALSE, mgt = FALSE, uniformity = FALSE)

# Without y axis limits adjustment
plot(fit1, limits = FALSE)
plot(fit2, limits = FALSE)

```

---

|     |                                |
|-----|--------------------------------|
| t50 | <i>Median germination time</i> |
|-----|--------------------------------|

---

### Description

Compute the median germination time ( $t_{50}$ ). Median germination time is the time to reach 50% of final/maximum germination.

### Usage

```
t50(germ.counts, intervals, partial = TRUE, method = c("coolbear", "farooq"))
```

### Arguments

|             |   |
|-------------|---|
| germ.counts | Germination counts at each time interval. Can be partial or cumulative as specified in the argument partial.          |
| intervals   | The time intervals.   |
| partial     | logical. If TRUE, germ.counts is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE. |
| method      | The method for computing median germination time. Either "coolbear" or "farooq".                                      |

### Details

With argument method specified as "coolbear", median germination time is computed according to the formula by Coolbear et al. (1984) as follows.

$$t_{50} = T_i + \frac{(\frac{N+1}{2} - N_i)(T_j - T_i)}{N_j - N_i}$$

Where,  $t_{50}$  is the median germination time,  $N$  is the final number of germinated seeds, and  $N_i$  and  $N_j$  are the total number of seeds germinated in adjacent counts at time  $T_i$  and  $T_j$  respectively, when  $N_i < \frac{N+1}{2} < N_j$ .

Similarly with argument method specified as "farooq", median germination time is computed according to the formula by Farooq et al. (2005) as follows.

$$t_{50} = T_i + \frac{(\frac{N}{2} - N_i)(T_j - T_i)}{N_j - N_i}$$

Where,  $t_{50}$  is the median germination time,  $N$  is the final number of germinated seeds, and  $N_i$  and  $N_j$  are the total number of seeds germinated in adjacent counts at time  $T_i$  and  $T_j$  respectively, when  $N_i < \frac{N}{2} < N_j$ .

Value

The median germination time ( $t_{50}$ ) value in the same unit of time as specified in the argument intervals.

References

Coolbear P, Francis A, Grierson D (1984). “The effect of low temperature pre-sowing treatment on the germination performance and membrane integrity of artificially aged tomato seeds.” *Journal of Experimental Botany*, **35**(11), 1609–1617.

Farooq M, Basra SMA, Ahmad N, Hafeez K (2005). “Thermal hardening: A new seed vigor enhancement tool in rice.” *Journal of Integrative Plant Biology*, **47**(2), 187–193.

See Also

[MeanGermRate](#)

Examples

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)

# From partial germination counts
#-----
t50(germ.counts = x, intervals = int, method = "coolbear")
t50(germ.counts = x, intervals = int, method = "farooq")

# From cumulative germination counts
#-----
t50(germ.counts = y, intervals = int, partial = FALSE, method = "coolbear")
t50(germ.counts = y, intervals = int, partial = FALSE, method = "farooq")
```

---

|              |                       |
|--------------|-----------------------|
| TimsonsIndex | <i>Timson's index</i> |
|--------------|-----------------------|

---

Description

Compute George’s index (George 1961; Tucker and Wright 1965; Nichols and Heydecker 1968; Chopra and Chaudhary 1980), Timson’s index or Timson’s germination velocity index (Grose and Zimmer 1958; Timson 1965; Lyon and Coffelt 1966; Chaudhary and Ghildyal 1970; Negm and Smith 1978; Brown and Mayer 1988; Baskin and Baskin 1998) and it’s modifications by Labouriau (Ranal and de Santana 2006) and (Khan and Ungar 1984).

**Usage**

```
TimsonsIndex(
  germ.counts,
  intervals,
  partial = TRUE,
  total.seeds,
  max,
  modification = c("none", "labouriau", "khanungar")
)

GermRateGeorge(germ.counts, intervals, partial = TRUE, max)
```

**Arguments**

|              |   |
|--------------|---|
| germ.counts  | Germination counts at each time interval. Can be partial or cumulative as specified in the argument partial.          |
| intervals    | The time intervals.   |
| partial      | logical. If TRUE, germ.counts is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE. |
| total.seeds  | Total number of seeds.  |
| max          | The maximum interval value up to which Timson's index/George's germination rate is to be computed.                    |
| modification | The modification to be applied. Either "none", "labouriau" or "khanungar". Default is "none" (see <b>Details</b> ).   |

**Details**

Timson's index (Timson 1965) is computed as follows (Grose and Zimmer 1958; Brown and Mayer 1988; Baskin and Baskin 1998).

$$\Sigma k = \sum_{i=1}^k G_i$$

Where,  $G_i$  is the cumulative germination percentage in time interval  $i$  and  $k$  is the total number of time intervals.

For example ten summation ( $\Sigma 10$ ) is expressed as follows.

$$\Sigma 10 = G_1 + G_2 + \dots + G_{10}$$

Where  $G_1, G_2, \dots, G_{10}$  are the cumulative germination percentage at day 1, 2, 3,  $\dots$ , 10 respectively. Similarly  $\Sigma 5$  or  $\Sigma 20$  can be estimated. For  $\Sigma 10$ , the value can range from 0 (no germination) to 1,000 (100% germination after 24 hours).

It is the progressive total of cumulative germination percentage recorded at specific intervals for a set period of time. It combines onset, rate and total percentage of germination and estimates the area under the cumulative germination percentage curve. It is same as the indices for area under time course curve of germination described by Lyon and Coffelt (1966) as well as Negm and Smith (1978). It is also described as Emergence Rate Index (*ERI*) by Chaudhary and Ghildyal (1970).

Goodchild and Walker (1971), described the same in terms of partial germination percentage as follows.

$$\Sigma k = \sum_{i=1}^k g_i(k-j)$$

Where,  $g_i$  is the germination (not cumulative, but partial germination) in time interval  $i$  ( $i$  varying from 0 to  $k$ ),  $k$  is the total number of time intervals, and  $j = i - 1$ .

Timson's index is equivalent to the Germination Energy Index  $GEI$  proposed by Grose and Zimmer (1958).

As Timson's index is useful for comparison only when samples have similar germinabilities or final germination percentage, the following modification was suggested by Labouriau (Ranal and de Santana 2006).

$$\Sigma k_{mod} = \frac{\Sigma k}{\sum_{i=1}^k g_i}$$

Here Timson's index ( $\Sigma k$ ) is divided by the sum of partial germination percentages.

Similarly another modification was proposed by (Khan and Ungar 1984), where Timson's index ( $\Sigma k$ ) is divided by the total time period of germination ( $T_k$ ).

$$\Sigma k_{mod} = \frac{\Sigma k}{T_k}$$

Timson's index is similar to the Germination Rate ( $GR$ ) proposed by George (1961) as follows (Tucker and Wright 1965; Nichols and Heydecker 1968).

$$GR = \sum_{i=1}^k N_i K_i$$

Where  $N_i$  is the number of seeds germinated by  $i$ th interval,  $K_i$  is the number of intervals(e.g. days) until the end of the test, and  $k$  is the total number of time intervals.

This index uses number of seeds germinated instead of germination percentage. It is also described as Emergence Rate Index ( $ERI$ ) by Chopra and Chaudhary (1980).

So germination rate ( $GR$ ) can also be described in terms of partial ( $N_i$ ) and cumulative ( $\sum_{j=1}^i N_j$ ) number of seeds germinated in each time interval ( $i$ ) as follows.

$$GR = \sum_{i=1}^k \sum_{j=1}^i N_j$$

$$GR = \sum_{i=1}^k N_i(k-j)$$

## Value

For TimsonsIndex The value of Timson's index.

For GermRateGeorge The value of George's germination rate.

## References

- Baskin CC, Baskin JM (1998). *Seeds: Ecology, Biogeography, and Evolution of Dormancy and Germination*. Academic Press, San Diego. ISBN 0-12-080260-0.
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- Grose RJ, Zimmer WJ (1958). "Some laboratory germination responses of the seeds of river red gum, *Eucalyptus camaldulensis* Dehn. Syn. *Eucalyptus rostrata* Schlecht." *Australian Journal of Botany*, **6**(2), 129.
- Khan MA, Ungar IA (1984). "The effect of salinity and temperature on the germination of polymorphic seeds and growth of *Atriplex triangularis* Willd." *American Journal of Botany*, **71**(4), 481–489.
- Lyon JL, Coffelt RJ (1966). "Rapid method for determining numerical indexes for time-course curves." *Nature*, **211**(5046), 330–330.
- Negm FB, Smith OE (1978). "Effects of Ethylene and Carbon Dioxide on the Germination of Osmotically Inhibited Lettuce Seed." *Plant Physiology*, **62**(4), 473–476.
- Nichols MA, Heydecker W (1968). "Two approaches to the study of germination data." *Proceedings of the International Seed Testing Association*, **33**(3), 531–540.
- Ranal MA, de Santana DG (2006). "How and why to measure the germination process?" *Brazilian Journal of Botany*, **29**(1), 1–11.
- Timson J (1965). "New Method of Recording Germination Data." *Nature*, **207**(4993), 216.
- Tucker H, Wright LN (1965). "Estimating rapidity of germination." *Crop Science*, **5**(5), 398–399.

## Examples

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)

# From partial germination counts
#-----
# Without max specified
TimsonsIndex(germ.counts = x, intervals = int, total.seeds = 50)
```

```

TimsonsIndex(germ.counts = x, intervals = int, total.seeds = 50,
  modification = "none")
TimsonsIndex(germ.counts = x, intervals = int, total.seeds = 50,
  modification = "labouriau")
TimsonsIndex(germ.counts = x, intervals = int, total.seeds = 50,
  modification = "khanungar")
GermRateGeorge(germ.counts = x, intervals = int)

# With max specified
TimsonsIndex(germ.counts = x, intervals = int, total.seeds = 50, max = 10)
TimsonsIndex(germ.counts = x, intervals = int, total.seeds = 50,
  max = 10, modification = "none")
TimsonsIndex(germ.counts = x, intervals = int, total.seeds = 50,
  max = 10, modification = "labouriau")
TimsonsIndex(germ.counts = x, intervals = int, total.seeds = 50,
  max = 10, modification = "khanungar")
GermRateGeorge(germ.counts = x, intervals = int, max = 10)
GermRateGeorge(germ.counts = x, intervals = int, max = 14)

# From cumulative germination counts
#-----
# Wihout max specified
TimsonsIndex(germ.counts = y, intervals = int, partial = FALSE,
  total.seeds = 50)
TimsonsIndex(germ.counts = y, intervals = int, partial = FALSE,
  total.seeds = 50,
  modification = "none")
TimsonsIndex(germ.counts = y, intervals = int, partial = FALSE,
  total.seeds = 50,
  modification = "labouriau")
TimsonsIndex(germ.counts = y, intervals = int, partial = FALSE,
  total.seeds = 50,
  modification = "khanungar")
GermRateGeorge(germ.counts = y, intervals = int, partial = FALSE,)

# With max specified
TimsonsIndex(germ.counts = y, intervals = int, partial = FALSE,
  total.seeds = 50, max = 10)
TimsonsIndex(germ.counts = y, intervals = int, partial = FALSE,
  total.seeds = 50,
  max = 10, modification = "none")
TimsonsIndex(germ.counts = y, intervals = int, partial = FALSE,
  total.seeds = 50,
  max = 10, modification = "labouriau")
TimsonsIndex(germ.counts = y, intervals = int, partial = FALSE,
  total.seeds = 50,
  max = 10, modification = "khanungar")
GermRateGeorge(germ.counts = y, intervals = int, partial = FALSE,
  max = 10)
GermRateGeorge(germ.counts = y, intervals = int, partial = FALSE,
  max = 14)

```

---

WeightGermPercent

---

*Weighted germination percentage*


---



## Description

Compute the Weighted germination percentage *WGP* or Weighted germination index *WGI* (Reddy 1978; Reddy et al. 1985).

## Usage

```
WeightGermPercent(germ.counts, total.seeds, intervals, partial = TRUE)
```

## Arguments

|                          |  |
|--------------------------|--|
| <code>germ.counts</code> | Germination counts at each time interval. Can be partial or cumulative as specified in the argument <code>partial</code> .         |
| <code>total.seeds</code> | Total number of seeds tested.  |
| <code>intervals</code>   | The time intervals.  |
| <code>partial</code>     | logical. If TRUE, <code>germ.counts</code> is considered as partial and if FALSE, it is considered as cumulative. Default is TRUE. |

## Details

Weighted germination percentage was calculated by giving maximum weight to the seeds that germinate first and decreasing weight to the seeds that germinate subsequently. It is computed as follows (Reddy 1978; Reddy et al. 1985).

$$WGP = \frac{\sum_{i=1}^k (k - i + 1)N_i}{k \times N} \times 100$$

Where,  $N_i$  is the number of seeds that germinated in the time interval  $i$  (not cumulative, but partial count),  $N$  is the total number of seeds tested, and  $k$  is the total number of time intervals.

## Value

The weighted germination percentage (%) value.

## References

Reddy LV (1978). *Effect of temperature on seed dormancy and alpha-amylase activity during kernel maturation and germination in wheat (Triticum aestivum L.) cultivars*. Ph.D. Thesis, Oregon State University.

Reddy LV, Metzger RJ, Ching TM (1985). "Effect of temperature on seed dormancy of wheat." *Crop Science*, **25**(3), 455.

## Examples

```
x <- c(0, 0, 0, 0, 4, 17, 10, 7, 1, 0, 1, 0, 0, 0)
y <- c(0, 0, 0, 0, 4, 21, 31, 38, 39, 39, 40, 40, 40, 40)
int <- 1:length(x)

# From partial germination counts
#-----
WeightGermPercent(germ.counts = x, total.seeds = 50, intervals = int)

# From cumulative germination counts
```

```
#-----  
WeightGermPercent(germ.counts = y, total.seeds = 50, intervals = int,  
                  partial = FALSE)
```

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