

2015

## Nonparametric Pairwise Multiple Comparisons in Independent Groups Using Dunn's Test

Alexis Dinno

*Portland State University*, [alexis.dinno@pdx.edu](mailto:alexis.dinno@pdx.edu)

Let us know how access to this document benefits you.

Follow this and additional works at: [https://pdxscholar.library.pdx.edu/commhealth\\_fac](https://pdxscholar.library.pdx.edu/commhealth_fac)



Part of the [Community Health Commons](#)

---

### Citation Details

Dinno, A. 2015. Nonparametric pairwise multiple comparisons in independent groups using Dunn's test. *Stata Journal* 15: 292-300.

This Article is brought to you for free and open access. It has been accepted for inclusion in Community Health Faculty Publications and Presentations by an authorized administrator of PDXScholar. For more information, please contact [pdxscholar@pdx.edu](mailto:pdxscholar@pdx.edu).

# THE STATA JOURNAL

## Editors

H. JOSEPH NEWTON  
Department of Statistics  
Texas A&M University  
College Station, Texas  
editors@stata-journal.com

NICHOLAS J. COX  
Department of Geography  
Durham University  
Durham, UK  
editors@stata-journal.com

## Associate Editors

CHRISTOPHER F. BAUM, Boston College  
NATHANIEL BECK, New York University  
RINO BELLOCCO, Karolinska Institutet, Sweden, and  
University of Milano-Bicocca, Italy  
MAARTEN L. BUIS, University of Konstanz, Germany  
A. COLIN CAMERON, University of California–Davis  
MARIO A. CLEVES, University of Arkansas for  
Medical Sciences  
WILLIAM D. DUPONT, Vanderbilt University  
PHILIP ENDER, University of California–Los Angeles  
DAVID EPSTEIN, Columbia University  
ALLAN GREGORY, Queen's University  
JAMES HARDIN, University of South Carolina  
BEN JANN, University of Bern, Switzerland  
STEPHEN JENKINS, London School of Economics and  
Political Science  
ULRICH KOHLER, University of Potsdam, Germany

FRAUKE KREUTER, Univ. of Maryland–College Park  
PETER A. LACHENBRUCH, Oregon State University  
JENS LAURITSEN, Odense University Hospital  
STANLEY LEMESHOW, Ohio State University  
J. SCOTT LONG, Indiana University  
ROGER NEWSON, Imperial College, London  
AUSTIN NICHOLS, Urban Institute, Washington DC  
MARCELLO PAGANO, Harvard School of Public Health  
SOPHIA RABE-HESKETH, Univ. of California–Berkeley  
J. PATRICK ROYSTON, MRC Clinical Trials Unit,  
London  
PHILIP RYAN, University of Adelaide  
MARK E. SCHAFFER, Heriot-Watt Univ., Edinburgh  
JEROEN WEESIE, Utrecht University  
IAN WHITE, MRC Biostatistics Unit, Cambridge  
NICHOLAS J. G. WINTER, University of Virginia  
JEFFREY WOOLDRIDGE, Michigan State University

## Stata Press Editorial Manager

LISA GILMORE

## Stata Press Copy Editors

DAVID CULWELL, SHELBI SEINER, and DEIRDRE SKAGGS

The *Stata Journal* publishes reviewed papers together with shorter notes or comments, regular columns, book reviews, and other material of interest to Stata users. Examples of the types of papers include 1) expository papers that link the use of Stata commands or programs to associated principles, such as those that will serve as tutorials for users first encountering a new field of statistics or a major new technique; 2) papers that go “beyond the Stata manual” in explaining key features or uses of Stata that are of interest to intermediate or advanced users of Stata; 3) papers that discuss new commands or Stata programs of interest either to a wide spectrum of users (e.g., in data management or graphics) or to some large segment of Stata users (e.g., in survey statistics, survival analysis, panel analysis, or limited dependent variable modeling); 4) papers analyzing the statistical properties of new or existing estimators and tests in Stata; 5) papers that could be of interest or usefulness to researchers, especially in fields that are of practical importance but are not often included in texts or other journals, such as the use of Stata in managing datasets, especially large datasets, with advice from hard-won experience; and 6) papers of interest to those who teach, including Stata with topics such as extended examples of techniques and interpretation of results, simulations of statistical concepts, and overviews of subject areas.

The *Stata Journal* is indexed and abstracted by *CompuMath Citation Index*, *Current Contents/Social and Behavioral Sciences*, *RePEc: Research Papers in Economics*, *Science Citation Index Expanded* (also known as *SciSearch*), *Scopus*, and *Social Sciences Citation Index*.

For more information on the *Stata Journal*, including information for authors, see the webpage

<http://www.stata-journal.com>

**Subscriptions** are available from StataCorp, 4905 Lakeway Drive, College Station, Texas 77845, telephone 979-696-4600 or 800-STATA-PC, fax 979-696-4601, or online at

<http://www.stata.com/bookstore/sj.html>

**Subscription rates** listed below include both a printed and an electronic copy unless otherwise mentioned.

U.S. and Canada		Elsewhere	
<b>Printed &amp; electronic</b>		<b>Printed &amp; electronic</b>	
1-year subscription	\$115	1-year subscription	\$145
2-year subscription	\$210	2-year subscription	\$270
3-year subscription	\$285	3-year subscription	\$375
1-year student subscription	\$ 85	1-year student subscription	\$115
1-year institutional subscription	\$345	1-year institutional subscription	\$375
2-year institutional subscription	\$625	2-year institutional subscription	\$685
3-year institutional subscription	\$875	3-year institutional subscription	\$965
<b>Electronic only</b>		<b>Electronic only</b>	
1-year subscription	\$ 85	1-year subscription	\$ 85
2-year subscription	\$155	2-year subscription	\$155
3-year subscription	\$215	3-year subscription	\$215
1-year student subscription	\$ 55	1-year student subscription	\$ 55

Back issues of the *Stata Journal* may be ordered online at

<http://www.stata.com/bookstore/sjj.html>

Individual articles three or more years old may be accessed online without charge. More recent articles may be ordered online.

<http://www.stata-journal.com/archives.html>

The *Stata Journal* is published quarterly by the Stata Press, College Station, Texas, USA.

Address changes should be sent to the *Stata Journal*, StataCorp, 4905 Lakeway Drive, College Station, TX 77845, USA, or emailed to [sj@stata.com](mailto:sj@stata.com).



Copyright © 2015 by StataCorp LP

**Copyright Statement:** The *Stata Journal* and the contents of the supporting files (programs, datasets, and help files) are copyright © by StataCorp LP. The contents of the supporting files (programs, datasets, and help files) may be copied or reproduced by any means whatsoever, in whole or in part, as long as any copy or reproduction includes attribution to both (1) the author and (2) the *Stata Journal*.

The articles appearing in the *Stata Journal* may be copied or reproduced as printed copies, in whole or in part, as long as any copy or reproduction includes attribution to both (1) the author and (2) the *Stata Journal*.

Written permission must be obtained from StataCorp if you wish to make electronic copies of the insertions. This precludes placing electronic copies of the *Stata Journal*, in whole or in part, on publicly accessible websites, file servers, or other locations where the copy may be accessed by anyone other than the subscriber.

Users of any of the software, ideas, data, or other materials published in the *Stata Journal* or the supporting files understand that such use is made without warranty of any kind, by either the *Stata Journal*, the author, or StataCorp. In particular, there is no warranty of fitness of purpose or merchantability, nor for special, incidental, or consequential damages such as loss of profits. The purpose of the *Stata Journal* is to promote free communication among Stata users.

The *Stata Journal* (ISSN 1536-867X) is a publication of Stata Press. Stata, **STATA**, Stata Press, Mata, **MATA**, and NetCourse are registered trademarks of StataCorp LP.

# Nonparametric pairwise multiple comparisons in independent groups using Dunn’s test

Alexis Dinno  
School of Community Health  
Portland State University  
Portland, OR  
alexis.dinno@pdx.edu

**Abstract.** Dunn’s test is the appropriate nonparametric pairwise multiple-comparison procedure when a Kruskal–Wallis test is rejected, and it is now implemented for Stata in the `dunntest` command. `dunntest` produces multiple comparisons following a Kruskal–Wallis  $k$ -way test by using Stata’s built-in `kwallis` command. It includes options to control the familywise error rate by using Dunn’s proposed Bonferroni adjustment, the Šidák adjustment, the Holm stepwise adjustment, or the Holm–Šidák stepwise adjustment. There is also an option to control the false discovery rate using the Benjamini–Hochberg stepwise adjustment.

**Keywords:** `st0381`, `dunntest`, `kwallis`, Dunn’s test, Kruskal–Wallis test, multiple comparisons, familywise error rate, Bonferroni, Šidák, Holm, Holm–Šidák, false discovery rate

## 1 Introduction

One-way omnibus tests, such as the common one-way analysis of variance (ANOVA), typically pose null hypotheses that measurements across some number of groups are all derived from a common distribution. One might think of such tests answering generic questions like, Does one need to bother looking more closely between groups for differences? Without evidence to reject the null hypothesis of such tests, one’s work moves on to new topics. On the other hand, if the null hypothesis of an omnibus test is rejected, the question becomes, Which of these groups is different from which? If one used an ANOVA to test for mean difference, upon rejection of the null hypothesis, one would make multiple pairwise comparisons using  $t$  tests for mean difference in unpaired data. However, the ANOVA has restrictive assumptions concerning the distributions of the groups under scrutiny: the groups must have equal variances, and the measures in each group must be continuous, normally distributed variables.

The nonparametric Kruskal–Wallis test (Kruskal and Wallis 1952) is a nonparametric analog to the one-way ANOVA that sacrifices the precision of discriminating means for the discrimination of stochastic dominance (that is, the probability that a randomly drawn observation from one group will be greater than a randomly drawn observation from another). However, the test can do so regardless of how the measures are distributed in each group. If one assumes that the measures are continuous and that the unspecified distributions in each group differ only in their centrality, then one can under-

stand the Kruskal–Wallis test as an omnibus test for median difference. Upon rejection of the null hypothesis of this test, one would conduct multiple pairwise comparisons for stochastic dominance or median difference.

It is clear that the appropriate test for such comparisons is a nonparametric analog to the  $t$  test—the rank-sum test (Wilcoxon 1945; Mann and Whitney 1947) is an example—but the application is not as straightforward. One can use ANOVA’s strict assumption about equal variances with the  $t$  tests that follow rejection of the null hypothesis of an ANOVA by using the pooled estimate of variance when calculating the standard error of the  $t$  test statistics. If one used a Kruskal–Wallis test, one would ignore this assumption, which is important when interpreting the median difference but more important when interpreting the rank-sum test as part of a family of inferences in the omnibus hypothesis. The ranks of the data on which the tests are based change if they are reranked in a pairwise fashion. Dunn’s (1964) insight was to retain the rank sums from the omnibus test and to approximate a  $z$ -test statistic to the exact rank-sum statistic. Dunn’s test is the appropriate procedure following a Kruskal–Wallis test.

Making multiple pairwise comparisons following an omnibus test redefines the meaning of  $\alpha$ , which usually represents the probability of falsely rejecting the null hypothesis for one test, within the inferential framework of the hypothesis test. Dunn (1961) described how to address this issue with a Bonferroni adjustment, which can modify the rejection level for any test by dividing  $\alpha$  by the total number of tests and requires a much smaller  $p$ -value to reject any test. This adjustment leaves  $\alpha$  numerically intact but multiplies the  $p$ -value. This forms the basis of the familywise error rate (FWER) redefinition of  $\alpha$  to signify the probability of falsely rejecting the null hypothesis in one test out of all tests performed. The Bonferroni adjustment introduced the FWER, but additional improvements followed: the Šidák (1967) adjustment, which is a slightly more powerful yet similar approach; Holm’s sequential adjustment; and the Holm–Šidák (1979) sequential adjustment, sometimes credited to Holland and Copenhaver (1988), which treats subsequent pairwise hypothesis tests as parts of different families on the basis of whether previous tests were rejected. Finally, Benjamini and Hochberg (1995) reasoned that  $\alpha$  should be interpreted as a desired false discovery rate (FDR) and should reflect how the expected rate of false discoveries changes after some pairwise tests are rejected in sequence.

Dunn’s (1964) test has grown in popularity over the past two decades (figure 1).<sup>1</sup> The test is frequently used with multiple-comparison adjustments. During the past two decades, out of 1,097 cited articles, 778 included the term “Bonferroni”, 11 included the term “Sidak” and excluded the term “Holm–Sidak”, 111 included the term “Holm” and excluded the term “Holm–Sidak”, 183 included the term “Holm–Sidak” (none included “Holland” and “Copenhaver”), and 14 included the terms “Benjamini” and “Hochberg”. Dunn’s increasingly used test is now implemented for Stata.

---

1. Data from a search on 6 March 2014 of Google Scholar for citations with the exact phrase “Dunn’s test” for each of the years 1994–2013.

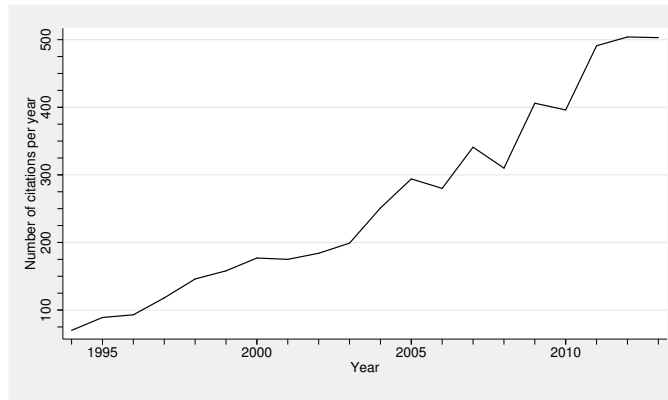


Figure 1. Citations indexed by Google Scholar including “Dunn’s test” over two decades

## 2 The `dunntest` command

### 2.1 Syntax

```
dunntest varname [if] [in], by(groupvar) [ma(method) nokwallis nolabel
    wrap level(#) ]
```

### 2.2 Description

`dunntest` reports the results of Dunn’s (1964) test for stochastic dominance among multiple pairwise comparisons following a Kruskal–Wallis test of stochastic dominance among  $k$  groups Kruskal and Wallis (1952) using `kwallis` (see [R] `kwallis`). `dunntest` performs  $m = k(k - 1)/2$  multiple pairwise comparisons using  $z$ -test statistics. The null hypothesis in each pairwise comparison is that the probability of observing a random value in the first group that is larger than a random value in the second group equals one half; this null hypothesis corresponds to that of the Wilcoxon–Mann–Whitney rank-sum test (see [R] `ranksum`, and note that the `porder` option provides an explicit estimate of this probability). As in the rank-sum test, if the data are assumed to be continuous and the distributions are assumed to be identical except for a shift in centrality, Dunn’s (1964) test may be understood as a test for median difference. In the syntax diagram above, *varname* refers to the variable recording the outcome, and *groupvar* refers to the variable denoting the population. `dunntest` accounts for tied ranks. `by()` is required.

### 2.3 Options

`by(groupvar)` specifies a variable that identifies the groups. `by()` is required.

`ma(method)` specifies the method of adjustment used for multiple comparisons and takes one of the following values: `none`, `bonferroni`, `sidak`, `holm`, `hs`, or `bh`. The default is `ma(none)`. These methods perform as follows:

`none` specifies that no adjustment for multiple comparisons be made.

`bonferroni` specifies a Bonferroni adjustment where the FWER is adjusted by multiplying the  $p$ -values in each pairwise test by  $m$  (the total number of pairwise tests). Stata will report a maximum Bonferroni-adjusted  $p$ -value of 1.

`sidak` specifies a Šidák adjustment where the FWER is adjusted by replacing the  $p$ -value of each pairwise test with  $1 - (1 - p)^m$  according to Šidák (1967). Stata will report a maximum Šidák-adjusted  $p$ -value of 1.

`holm` specifies a Holm adjustment where the FWER is adjusted sequentially by adjusting the  $p$ -values of each pairwise test, ordered from smallest to largest, with  $p(m + 1 - i)$ , where  $i$  is the position in the ordering according to Holm (1979). Stata will report a maximum Holm-adjusted  $p$ -value of 1. Because the decision to reject the null hypothesis in sequential tests depends both on the  $p$ -values and how they are ordered, the comparisons rejected by this method at the alpha level (two-sided test) are underlined in the output.

`hs` specifies a Holm–Šidák adjustment where the FWER is adjusted sequentially by adjusting the  $p$ -values of each pairwise test, ordered from smallest to largest, with  $1 - (1 - p)^{m+1-i}$ , where  $i$  is the position in the ordering according to Holm (1979). Stata will report a maximum Holm–Šidák-adjusted  $p$ -value of 1. Because the decision to reject the null hypothesis in sequential tests depends both on the  $p$ -values and how they are ordered, the comparisons rejected by this method at the alpha level (two-sided tests) are underlined in the output.

`bh` specifies a Benjamini–Hochberg adjustment where the FDR is adjusted sequentially by adjusting the  $p$ -values of each pairwise test, ordered from largest to smallest, with  $p\{m/(m + 1 - i)\}$ , where  $i$  is the position in the ordering according to Benjamini and Hochberg (1995). Stata will report a maximum Benjamini–Hochberg-adjusted  $p$ -value of 1. Such FDR-adjusted  $p$ -values are sometimes called  $q$ -values. Because the decision to reject the null hypothesis in sequential tests depends on both the  $p$ -values and how they are ordered, the comparisons rejected by this method at the alpha level (two-sided test) are underlined in the output.

`nokwallis` suppresses the display of the Kruskal–Wallis test table.

`nolabel` causes the Dunn’s test tables to display the actual data codes rather than the value labels.

`wrap` requests that Stata not break up wide tables to make them readable.

`level(#)` specifies the compliment of  $\alpha \times 100$ . The default is `level(95)` (or as set by `set level [see [R] level]`) and corresponds to  $\alpha = 0.05$ .

## 2.4 Stored results

`dunntest` stores the following in `r()`:

Scalars			
<code>r(df)</code>	degrees of freedom for the Kruskal–Wallis test	<code>r(chi2_adj)</code>	$\chi^2$ adjusted for ties for the Kruskal–Wallis test
Matrices			
<code>r(Z)</code>	vector of Dunn’s $z$ -test statistics	<code>r(P)</code>	vector of (possibly adjusted) $p$ -values for Dunn’s $z$ -test statistics

## 3 Remarks

### ► Example 1

Stata comes with data from the 1980 U.S. Census, and the documentation for the `kwallis` command works through an example to test whether the variable `medage` (median age of the population) varies by the variable `region` (Northeast, North Central, South, and West). The `dunntest` command defaults to presenting output from the omnibus `kwallis` command and follows it with a table of pairwise comparisons.

```
. sysuse census
(1980 Census data by state)
. dunntest medage, by(region) ma(none)
Kruskal-Wallis equality-of-populations rank test
```

region	Obs	Rank Sum
NE	9	376.50
N Cntrl	12	294.00
South	16	398.00
West	13	206.50

```
chi-squared = 17.041 with 3 d.f.
probability = 0.0007
chi-squared with ties = 17.062 with 3 d.f.
probability = 0.0007
```

Comparison of medage by region  
(No adjustment)

Row Mean- Col Mean	NE	N Cntrl	South
N Cntrl	2.698212 0.0035		
South	2.793742 0.0026	-0.067405 0.4731	
West	4.107611 0.0000	1.477266 0.0698	1.652733 0.0492



The `kwallis` output appears as it does in the example in the manual. Below the output, there is a table that provides all six pairwise comparisons for the four regions. The table's title indicates the *varname* and *groupname*, and the subtitle indicates which method of adjustment is used (in this example, `dunntest` has defaulted to No adjustment). The row and column header labels indicate that the test results are based on the difference in mean ranks for each group, and the table entries give the pairwise  $z$ -test statistics with  $p$ -values beneath.

◀

### ► Example 2

Suppose one wants to adjust for multiple comparisons using the Holm–Šidák adjustment.

```
. sysuse census
(1980 Census data by state)
. dunntest medage, by(region) nokwallis ma(hs)

                Comparison of medage by region
                (Holm-Sidk)
```

Row Mean- Col Mean	NE	N Cntrl	South
N Cntrl	2.698212 <u>0.0139</u>		
South	2.793742 <u>0.0130</u>	-0.067405 0.4731	
West	4.107611 <u>0.0001</u>	1.477266 0.1347	1.652733 0.1404

Because `ma(hs)` was included as an option, the  $p$ -values of the tests rejected for a FWER of  $\alpha = 0.05$  are underlined.

◀

### ► Example 3

In her 1964 article, Dunn included frequencies of individuals in seven broad occupational categories (for example, executives and sharecroppers) and the individuals' eligibility for home care defined by three exclusive categories (eligible for home care, ineligible for home care because of the lack of a responsible person, ineligible for home care because of the unavailability of a responsible person). She used these data in an analysis to illustrate her new test. She applied her test theory both to linear combinations between groups and to pairwise differences of mean ranks. In her worked example, she presented the results for only one pairwise test concerning whether occupational class among those with eligible home care is stochastically dominant over the occupational class of those for whom a responsible person is unavailable. We tested her data using `dunntest`, and our figures agree precisely with her results.

```
. use homecare
(Occupation and Home Care Eligibility for 383 Patients)
. dunnstest occupation, by(eligibility) ma(none) nokwallis

Comparison of occupation by eligibility
(No adjustment)
```

Row Mean- Col Mean	Eligible	No respo
No respo	-0.155969 0.4380	
Responsi	-2.022198 0.0216	-1.441206 0.0748

◀

## 4 Methods

### 4.1 Dunn's test

Dunn's  $z$ -test statistic (1) approximates exact rank-sum test statistics by using the mean rankings of the outcome in each group from the preceding Kruskal–Wallis test ( $\bar{W}_i = W_i/n_i$ , where  $W_i$  is the sum of ranks, and  $n_i$  is the sample size for the  $i$ th group) and basing inference on the differences in mean ranks in each group. To compare group  $A$  with group  $B$ , we calculate

$$z_i = \frac{y_i}{\sigma_i} \quad (1)$$

where  $i$  is one of the 1 to  $m$  multiple comparisons,  $y_i = \bar{W}_A - \bar{W}_B$ , and  $\sigma_i$  is the standard deviation of  $y_i$ , given by (2),

$$\sigma_i = \sqrt{\left\{ \frac{N(N+1)}{12} - \frac{\sum_{s=1}^r \tau_s^3 - \tau_s}{12(N-1)} \right\} \left( \frac{1}{n_A} + \frac{1}{n_B} \right)} \quad (2)$$

where  $N$  is the total number of observations across all groups,  $r$  is the number of tied ranks, and  $\tau_s$  is the number of observations tied at the  $s$ th specific tied value. When there are no ties, the term with the summation in the denominator equals zero, and the calculation of (2) simplifies considerably.

### 4.2 Multiple-comparison adjustments

Here we describe each of the multiple-comparison adjustment procedures.  $p^*$  indicates an adjusted  $p$ -value.  $p$  refers to  $p$ -values that have the standard two-sided test interpretation  $p = P(|Z| \geq |z|)$ .  $p_i$  refers to  $p$ -values as the order for the sequential procedures described below.

The Bonferroni adjustment multiplies each  $p$ -value by  $m$ , as shown in (3).

$$p^* = pm \quad (3)$$

The Šidák adjustment corrects the Bonferroni adjustment's error by defining the FWER and gives a slightly smaller  $p^*$ , as shown in (4).

$$p^* = 1 - (1 - p)^m \quad (4)$$

Holm's stepwise adjustment controls the FWER by ordering all  $m$   $p$ -values from smallest to largest, providing a Bonferroni adjustment based on  $i$  and  $m$ , and fails to reject all pairwise tests, starting with the first test for which  $p^* > \alpha/2$ , as shown in (5).

$$p_i^* = p(m + 1 - i) \quad (5)$$

The Holm–Šidák stepwise adjustment follows Holm's method but applies the Šidák adjustment based on  $i$  and  $m$ , as shown in (6).

$$p_i^* = 1 - (1 - p)^{(m+1-i)} \quad (6)$$

The Benjamini–Hochberg stepwise adjustment controls the FDR by ordering all  $m$   $p$ -values from largest to smallest and adjusting  $p$  by multiplying by  $m/(m + 1 - i)$ . It fails to reject all pairwise tests, starting with the first test for which  $p^* > \alpha/2$ , as shown in (7). Simes (1986) first described this adjustment procedure, or one very similar to it, but did not provide the FDR interpretation.

$$p_i^* = p \frac{m}{(m + 1 - i)} \quad (7)$$

## 5 References

- Benjamini, Y., and Y. Hochberg. 1995. Controlling the false discovery rate: A practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society, Series B* 57: 289–300.
- Dunn, O. J. 1961. Multiple comparisons among means. *Journal of the American Statistical Association* 56: 52–64.
- . 1964. Multiple comparisons using rank sums. *Technometrics* 6: 241–252.
- Holland, B. S., and M. D. Copenhaver. 1988. Improved Bonferroni-type multiple testing procedures. *Psychological Bulletin* 104: 145–149.
- Holm, S. 1979. A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics* 6: 65–70.
- Kruskal, W. H., and W. A. Wallis. 1952. Use of ranks in one-criterion variance analysis. *Journal of the American Statistical Association* 47: 583–621.

Mann, H. B., and D. R. Whitney. 1947. On a test of whether one of two random variables is stochastically larger than the other. *Annals of Mathematical Statistics* 18: 50–60.

Šidák, Z. 1967. Rectangular confidence regions for the means of multivariate normal distributions. *Journal of the American Statistical Association* 62: 626–633.

Simes, R. J. 1986. An improved Bonferroni procedure for multiple tests of significance. *Biometrika* 73: 751–754.

Wilcoxon, F. 1945. Individual comparisons by ranking methods. *Biometrics Bulletin* 1: 80–83.

#### **About the author**

Alexis Dinno is an assistant professor at the school of Community Health at Portland State University. She is trained as a social epidemiologist with interests in applied quantitative methods, social ecology, and health equity. She wrote the `dunntest`, `dthaz`, `paran`, and `tost` packages.