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A COMPARISON OF GOODNESS-OF-FIT TESTS FOR ANALYSIS OF NEST ORIENTATION IN WESTERN KINGBIRDS (*TYRANNUS VERTICALIS*)[1]

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Abstract. Computer simulations and Western Kingbird (*Tyrannus verticalis*) nest orientation data were used to compare the properties and assumptions of four goodness-of-fit tests. The results and relative abilities of each test to detect different patterns of nest orientation were evaluated. The computer simulations showed that each method was powerful in detecting unimodal patterns. However, Rayleigh's Z and Watson's U^2 lacked the robustness for detecting bimodal patterns demonstrated by Rao's U. Computer simulations demonstrated a lack of robustness and low power in detecting directional avoidance patterns, but also demonstrated that each method performed with low Type I error and high power when analyzing data with no pattern.

Nest orientation of Western Kingbirds exhibited a high degree of variation between years, but appeared to be generally polymodal with modes in the north, south and east. The detection of a significant pattern of nest orientation was dependent on the analytical method used. Chi-square analysis showed significant departures from a uniform distribution in each of four years and all years combined. Rayleigh's Z indicated significant nest orientation only in 1986. Watson's U^2 and Rao's spacing test both indicated significant nest orientation for all years combined, and years 1985 (Rao's spacing test only) and 1986.

Rao's spacing test has distinct advantages in the analysis of nest orientation and other circular data over other commonly used goodness-of-fit tests, especially if the data are polymodal. Rao's spacing test accounts for many of the statistical implications a researcher must consider when analyzing nest orientation data. It is more flexible; able to handle more types of circular data with fewer limiting assumptions; can detect polymodality; and is more powerful with small sample sizes. In addition, the nest orientation of Western Kingbirds and other species is probably affected by multiple factors such as microclimate, predation and habitat structure which make the use of Rao's spacing test indespensible in determining the nature of the pattern of nest orientation of Western Kingbirds.

Key words: Nest orientation; circular distribution; goodness-of-fit tests; computer simulation; Rao's spacing test.

INTRODUCTION

Many studies have addressed the angular orientation of bird nests relative to a reference point such as a tree trunk or a slope (Ricklefs and Hainsworth 1969, Dennis 1971, Conner 1975, Raphael 1985, Grahm 1988), and several have concluded that some species exhibit non-uniform patterns of nest orientation relative to such a reference point (Austin 1974, Inouye 1976, McClelland 1977, Finch 1983, Korol and Hutto 1984). However, the appropriate statistical method for demonstrating such patterns remains unclear. The purpose of this paper is to compare the properties and assumptions of four goodness-of-fit methods for analyzing nest orientation data. Analysis of both simulated data with known patterns, and field data from breeding populations of the Western Kingbird (*Tyrannus verticalis*) will contrast the results of each statistical test under different sets of conditions. Possible explanations for the patterns of nest placement of Western Kingbirds are considered from the viewpoint of natural history and ecology.

The statistical analysis of angular or circular data differs from the analysis of linear data (Batschelet 1965, 1981; Mardia 1972; Zar 1984). For example, in circular data the calculation of a mean angle (ϕ) of orientation can rarely be accomplished by the simple summation of sample values and division by sample size (Note: for an example see Batschelet 1965). Because there is no true zero point, any designation of relative magnitude will be necessarily arbitrary (Zar 1984). Many different kinds of analysis of nest orientation data have been used, including graphical and tabular descriptions (Dennis 1971, Conner

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1975), calculations of simple statistics such as mean angle and variance (Austin 1974, Inouye 1976), and goodness-of-fit tests such as chi-square (Ricklefs and Hainsworth 1969), Watson's U^2 (Raphael 1985) and Rayleigh's Z (Finch 1983, Zerba and Morton 1983, Korol and Hutto 1984, Grahm 1988). However, certain of these analyses may prove inadequate because circular distributions do not often conform to the requirements or assumptions of the most commonly used statistical tests (Cain 1989). Thus, when choosing an appropriate statistical method for analyzing nest orientation data several factors must be carefully considered, including the consequences of grouping continuous data, assumptions about null hypotheses, and the expected alternative circular distribution.

Unlike linear distributions, which are often two-tailed and infinite, circular distributions exhibit finite closure because a circular data set comes back on itself, and therefore, 0° and 360° are actually the same point on a circle (Batschelet 1965, 1981; Mardia, 1972). When circular data are grouped, continuous data are divided into ranges of angles or arc segments, such as quadrants (90° arc segments) facing each major compass direction (see Fig. 1). Because of the finite closure of circular distributions, designation of groups and their alignment on the circle are necessarily arbitrary. Furthermore, when observations fall close to group divisions small shifts in either direction, as when converting from magnetic north to true north, can significantly alter group membership.

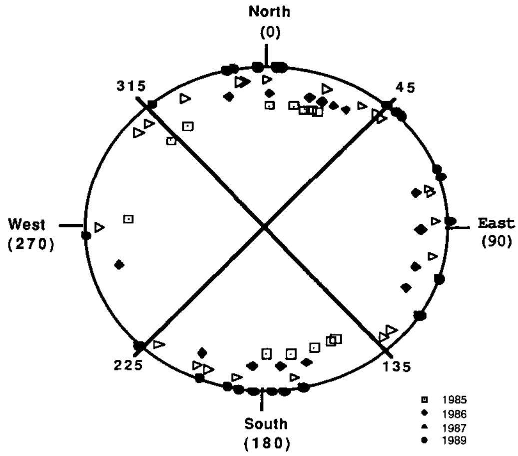

FIGURE 1. Nest orientation of Western Kingbird nests for years 1985, 1986, 1987 and 1989.

In most circular statistical analyses, the null hypothesis is a uniform distribution (which has often been used synonymously with randomness in the literature) in which all directions occur with equal probability (i.e., no mean direction; Batschelet 1981; Zar 1984). In contrast, most linear statistical analyses use a null hypothesis of randomness (i.e., a Poisson distribution), not uniformity (Zar 1984). A uniform distribution more adequately reflects the finite closure of a circle than a random distribution (Mardia 1972).

TABLE 1. Examples of different types of goodness of fit tests for circular data with type of data, minimum sample size (n), null distribution, test statistic formula, and other assumptions or restrictions given for each. In the following formulae, E = expected group size; O = observed group size; $u_i = a_i/360$; a_i = observed angle; i = rank of observed angle; n = sample size; $\hat{u}$ = mean of u_i; r = length of mean vector; $x = (\Sigma \cos a_i)/n$; $y = (\Sigma \sin a_i)/n$; $T_i = (a_i - a_{(i-1)})$.

Test	Data type	Null distribution	Formula	Assumptions/restrictions
Chi-Square	Grouped	χ^2	$\chi^2 = \Sigma [(E - O)^2/E]$	No. of groups between $n/15$ and $n/5$; No expected group (E) < 5; $n \geq 25$; Choice of groups independent of outcome.
Watson U^2	Continuous	Uniform	$U^2 = \Sigma u_i^2 - (\Sigma u_i)^2/n - 2/n \Sigma iu_i + (n + 1)\hat{u} + n/12$	Unimodal (von Mise) alternative distribution; $n \geq 5$.
Rayleigh Z	Continuous	Uniform	$Z = r^2/n$; $r = \sqrt{(x^2 + y^2)}$	Unimodal (von Mise) alternative distribution; $n \geq 5$.
Rao's U	Continuous	Uniform	$U = 1/2 \Sigma (\|T_i - 360/n\|)$	$n \geq 5$.

The alternative hypothesis or expected circular distribution of most goodness-of-fit tests (Table 1) is unimodal implying a single preferred direction or mean vector (r), and that a single factor or set of factors is operating to produce that preference. However, in the case of nest orientation this alternative may not be the case. Because of finite closure, circular distributions are more likely to be polymodal than linear distributions (Mardia 1972, Batschelet 1981), and multiple factors or sets of factors may influence nest placement (Hildén 1965, Walsberg 1985). Thus, many goodness-of-fit tests may be inappropriate for the analysis of nest orientation data or any type of circular data in which polymodal or directional avoidance distributions may be anticipated (Batschelet 1981).

METHODS

STATISTICAL ANALYSIS

Four tests of goodness-of-fit were considered in this paper: 1) chi-square (χ^2); 2) Rayleigh's Z; 3) Watson's U^2; and 4) Rao's spacing test. Each method has differing restrictions and assumptions which affect its ability to detect patterns of nest orientation. The type of data, minimum sample size, null distribution, test statistic formula, assumptions, and restrictive conditions for each goodness-of-fit test are given in Table 1. Specific descriptions, directions for test statistic caluculation, and significance tables for chi-sqare, Rayleigh's Z and Watson's U^2 are given in Batschelet (1965, 1981) and Zar (1984), and for Rao's spacing test are given in Rao (1969, 1976) and Batschelet (1981).

COMPUTER SIMULATIONS

Simulated data that approximated the von Mise distribution (i.e., circular normal data; Mardia 1972, Batschelet 1981) were created by randomly assigning points to data sets of different angular dispersion (k; i.e., parameter of concentration) and sample size (n). The proportion of significant simulations ($P = 0.05$) was determined for computer simulations of each specific set of conditions. Four different types of pattern were analyzed: unimodality; bimodality; directional avoidance and uniformity. Both sample size and angular dispersion (i.e., arc segments of different length) were varied within each pattern type (n = 5, 10, 20, 30, and 45; k = 20°, 45°, 90°, 135°, 180°) creating different sets of conditions. Type I and Type II error, power and an assessment of the robustness of three of the statistical methods (Watson's U^2; Rayleigh's Z and Rao's U) were determined under each set of conditions. Chi-square was not analyzed using computer simulation for reasons detailed in the discussion. All computer simulations were run on an IBM 370 and SAS (SAS Institute 1985).

NEST ORIENTATION

Field data were collected near Lake McConaughy, Keith County, Nebraska, during the breeding seasons of 1985, 1986, 1987, and 1989. Nest orientation was determined by standing next to the tree trunk; facing toward the nest; sighting with a hand-held compass along the line from the tree trunk to a spot marked on the ground directly below the nest; and recording the angle in degrees from magnetic north.

RESULTS

SIMULATED DATA

The results of the computer simulation analysis showed some similarities, but also some striking differences between each method. Each of the methods detected unimodal patterns with low Type II error and high power except at combinations of small sample size and wide angular dispersion (Table 2). Overall, Rao's U was somewhat better at detecting unimodal patterns at combinations of small sample size (n = 5) and wide angular dispersion (k = 135, 180), while Rayleigh's Z and Watson's U^2 performed similarly under all sets of conditions (Table 2).

Rayleigh's Z could not detect bimodal patterns (high Type II error) for any set of conditions (Table 2), while Watson's U^2 did detect bimodal patterns (low type II error) for larger data sets and narrow angular dispersion (Table 2). In contrast, Rao's U was powerful in detecting bimodal patterns (low Type II error) under most conditions except combinations of small sample size and wide angular dispersion (Table 2).

Patterns of directional avoidance were detected only at larger sample sizes and wide angular dispersion (Table 2), and each method exhibited high Type II error for all other sets of conditions. Watson's U^2 was somewhat better than Rayleigh's Z or Rao's U in detecting directional avoidance. For uniform data sets, each method accepted the null hypothesis of no pattern with low Type I error for all sets of conditions, al-

TABLE 2. The proportion of significant computer simulations ($n = 100$) for each statistical method and type of pattern: a) unimodal; b) bimodal; c) directional avoidance; and d) uniformity. Angular dispersion (k) or parameter of concentration is the arc segment that contains randomly selected data points. For a), b), c) the Type II error (β) = (1 − value in table); Power = (1 − β). For d) the Type I error = (value in table).

a) Unimodal

		Angular dispersion (k)				
	n	20	45	90	135	180
Watson's U^2	5	1.00	1.00	1.00	0.75	0.31
	10	1.00	1.00	1.00	1.00	0.89
	20	1.00	1.00	1.00	1.00	1.00
	30	1.00	1.00	1.00	1.00	1.00
	45	1.00	1.00	1.00	1.00	1.00
Rayleigh's Z	5	1.00	1.00	1.00	0.78	0.33
	10	1.00	1.00	1.00	1.00	0.87
	20	1.00	1.00	1.00	1.00	1.00
	30	1.00	1.00	1.00	1.00	1.00
	45	1.00	1.00	1.00	1.00	1.00
Rao's U	5	1.00	1.00	1.00	0.88	0.53
	10	1.00	1.00	1.00	1.00	1.00
	20	1.00	1.00	1.00	1.00	1.00
	30	1.00	1.00	1.00	1.00	1.00
	45	1.00	1.00	1.00	1.00	1.00

b) Bimodal

		Angular dispersion (k)				
	n	20	45	90	135	180
Watson's U^2	10	0.12	0.00	0.00	0.01	0.02
	20	1.00	1.00	0.06	0.00	0.02
	30	1.00	1.00	0.67	0.02	0.00
Rayleigh's Z	10	0.00	0.00	0.00	0.00	0.02
	20	0.00	0.00	0.00	0.00	0.01
	30	0.00	0.00	0.00	0.00	0.00
Rao's U	10	1.00	1.00	0.48	0.10	0.06
	20	1.00	1.00	1.00	0.70	0.19
	30	1.00	1.00	1.00	1.00	0.07

c) Directional avoidance

		Angular dispersion (k)			
	n	225	270	315	340
Watson's U^2	10	0.44	0.16	0.07	0.05
	20	0.98	0.36	0.12	0.08
	30	1.00	0.62	0.11	0.06
	45	1.00	0.98	0.21	0.04
Rayleigh's Z	10	0.49	0.14	0.05	0.03
	20	0.91	0.46	0.13	0.05
	30	0.99	0.67	0.18	0.09
	45	1.00	0.76	0.12	0.11
Rao's U	10	0.40	0.21	0.05	0.05
	20	0.81	0.38	0.14	0.08
	30	1.00	0.62	0.17	0.18
	45	1.00	0.71	0.22	0.06

d) Uniformity

n	Watson's U^2	Rayleigh's Z	Rao's U
5	0.04	0.05	0.05
10	0.03	0.04	0.05
20	0.03	0.03	0.04
30	0.03	0.03	0.01
45	0.02	0.02	0.01

TABLE 3. The mean angles (°) and length of the mean vectors (r) for nest orientation of *Tyrannus verticalis* for all years and 1985, 1986, 1987 and 1989.

Variable	All years	1985	1986	1987	1989
Sample size (n)	84	15	20	25	24
Mean angle (°)	74.60	22.50	69.50	83.80	91.30
Mean vector (r)	0.18	0.13	0.39	0.11	0.15

though Watson's U^2 was slightly better at small sample sizes and Rao's U slightly better at larger sample sizes (Table 2).

FIELD DATA

Most Western Kingbird nests (n = 84) were located on the north and south of the tree with somewhat fewer on the east. Few nests were found on the west side of the tree (Fig. 1). These patterns were consistent across years. The mean angle for each year was generally north to east with a range of 22.5°–91.3°, and the lengths of the mean vectors (r) were fairly small (Table 3). The data did not exhibit obvious unimodal directedness, and appeared to be polymodal, especially in 1985 and 1986.

The results from each of the goodness-of-fit tests show substantial differences. Chi-square indicated significant differences from a uniform distribution in every case, whereas Rayleigh Z indicated significance in only one year (1986). Watson's U^2 test indicated significant differences for all years combined, and for 1986. Likewise, Rao's spacing test indicated significant differences for all years combined, as well as for 1985 and 1986.

DISCUSSION

The analysis of computer simulations and the nest orientation of *T. verticalis* demonstrated that statistical significance was dependent on the type of data, and the restrictions or assumptions about data distributions applicable to each test. The computer simulations showed that three of the other goodness-of-fit methods were quite powerful in detecting unimodal patterns even at quite small sample sizes and wide angular dispersion. Overall, each method performed similarly except that Rao's U was somewhat better at very small sample size and at the widest angular dispersion. These results suggest that any of the methods would be effective in detecting unimodal patterns from field data. Of course, Watson's U^2 and Rayleigh's Z were designed to test for unimodal patterns and such results should be expected, yet Rao's U was not designed specifically for unimodal patterns, but performed equally well or better.

On the other hand, Rayleigh's Z and Watson's U^2 lack the robustness for detecting polymodal deviations from assumed uniformity demonstrated by Rao's U, primarily because they test for a specific alternative distribution—unimodality. While some species may exhibit single preferences others, such as Western Kingbirds, show no simple directional preference (Fig. 1) suggesting that multiple factors are involved. Given that the data are not unimodal, but bimodal, then an underlying assumption of Rayleigh's Z and Watson's U^2 is violated, and their use would be inappropriate.

Most goodness-of-fit methods test for a particular directional preference, but avoidance of a particular direction creates a different kind of distribution (in fact, inverted and opposite) which further complicates statistical analysis. Computer simulations for each of the methods demonstrated a lack of robustness or power for detecting directional avoidance except at large sample sizes and wide angular dispersion of avoidance. Because avoidance data lack information about a particular preference or mean vector (ϕ) and tests such as Rayleigh's Z and Watson's U^2 are based on deviation from a specific mean vector (ϕ), application of such tests to avoidance data again violates an underlying assumption making such tests ineffective and inappropriate. However, Rao's U was equally ineffective in detecting directional avoidance. Unfortunately, this suggests that directional avoidance may be difficult to detect with any of the methods unless the directional avoidance is widely dipersed.

The computer simulations suggest that each of the methods performs well when the data exhibit no pattern. The level of Type I error exhibited by each method was consistent with the predetermined level of significance (P = 0.05). This suggests that a researcher can be confident in each of the methods when no pattern is detected unless he suspects polymodality or directional avoidance. Of course, simulations of bimodal data for Watson's U^2 and Rayleigh's Z gave the same results—no significant pattern. In effect, Type I error is increased at the expense of Type II error when sample sizes are held constant (Steel and Torrie 1960, Zar 1984). This means that if the field data are actually bimodal then Type II error is very large and Rayleigh's Z and Watson's U^2 are likely to accept a false hypothesis—no pattern.

The field data exhibited a great deal of variation between years. This variation caused inconsistency in the results of the statistical analyses. Data from 1985 were clearly bimodal, yet Rayleigh's Z and Watson's U^2 did not detect a pattern. However, this is consistent with their inability to detect bimodality in the computer simulations. Data from 1986 appeared polymodal with clusters of observations in the North, East, and South quadrants (Fig. 1), and each method detected a significant pattern. These results would be consistent with a pattern of widely dispersed western avoidance (135°) and increased sample size ($n = 20$), which was indeed the case. Data from 1987 and 1989 also appear polymodal with clusters in the same general directions, but the angular dispersion of western avoidance is not as great, in fact less than 90°. Again, this is consistent with the results of the computer simulations and the failure of any method to detect directional avoidance under these sets of conditions. Data over all years exhibit the same general pattern of western avoidance, but the sample size is much greater giving Watson's U^2 and Rao's U sufficient power to detect significant patterns.

Chi-square results were influenced by arbitrary group alignment, which could reflect researcher bias. For example, by simply rotating the alignment of the group quadrants 45° (Fig. 1), the edges bisect the modes in the data distribution giving substantially different results from the original chi-square; no significant differences detected. Tests of individual years were inappropriate for the Western Kingbird data set and for many of the computer simulations due to sample size limitations. Although the number of designated groups could have been increased to alleviate the problem of arbitrary alignment, this would have lowered expected group membership. Larger sample sizes would ameliorate this problem but might not be possible in many cases. For example, designating eight groups would require a sample size of at least 40 to make a chi-square test appropriate.

Overall, in the analysis of nest orientation and other circular data, Rao's spacing test has distinct advantages over other commonly used goodness-of-fit tests, and accounts for many of the statistical considerations relevant to a researcher when analyzing nest orientation data. Rao's spacing test is often more powerful and more robust which enables it to handle different types of circular data, such as polymodality, with fewer limiting assumptions. In addition, Rao's spacing test is more sensitive to differences in sample size making fewer Type I and II errors which gives increased confidence in its results.

The detection of non-uniform nest orientation is a necessary pre-requisite to the investigation of factors affecting preferences and, in nature, nest orientation is probably affected by many factors. For example, microclimate within the tree canopy can have a significant influence on nest placement (Walsberg 1985). Radiation balance within the canopy is largely a composite of diurnal solar radiation and convective cooling due to wind. During the nesting season in western Nebraska, ambient temperatures reach >33°C during the hottest period of the day (2–5 pm) when the sun's azimuth is southwest to west, but can drop to <5°C during the night. Under normal conditions eggs lose 9–18% of initial mass through water loss during incubation (Drent 1975), but extreme temperatures increase this loss and can be fatal (Walsberg 1985). Also, direct solar radiation into the nest can produce lethal temperatures for both eggs and nestlings (Walsberg 1985).

In western Nebraska, wind direction is typically from the south to southwest during the nesting season. The low nightly temperatures combined with south to southwest winds can produce substantial convective cooling. The increased thermoregulatory energy demands during the night suggest the existence of selective pressure for birds to choose nest-sites that minimize thermoregulatory stress. Metabolic energy consumption in sheltered nest-sites can be reduced by 43% compared to exposed nest-sites (Walsberg 1985).

Thunderstorms produce high velocity winds which are capable of destroying a nest, and on one study site over four years, four nests were destroyed by thunderstorms (Bergin 1987). These storms typically come from the southwest producing southwest to westerly winds, and three of the four nests destroyed were on the west side of the tree. Thus, the avoidance of the west side of the tree canopy by Western Kingbirds in western Nebraska is consistent with avoidance of excessive diurnal heat gain (Balda and Bateman 1973), nocturnal heat loss (Walsberg 1985) and extreme wind velocity.

Predator avoidance may also affect nest placement (Murphy 1983, Blancher and Robertson 1985). Open-nesting birds are subject to a variety of nest predators including snakes, birds of prey, and scavengers such as the common grackle (*Quiscalus quiscula*). Some predators can remember nest sites from year to year (Sonerud 1982), and may key in on directional preferences of particular species. Such predator strategies would ultimately lead to either shifts in orientation preference or avoidance of past directional preferences.

Nest orientation preference or avoidance must be linked to environmental cues that allow discrimination among directions. These cues may include large scale factors such as the earth's magnetic field and solar azimuth, local scale factors such as local bodies of water, topographic features and habitat structure (Hildén 1965) or nest-site scale factors such as tree structure, floristics or microclimate. On the other hand, since statistical analysis must conform to assmptions of independence among obsevations, the researcher's alignment of a circular grid may not reflect cues relevant to individual birds. This is especially true when data are grouped, directions are avoided rather than prefered, or nest placement reflects existing habitat structure rather than a preference. For example, some species of trees have directional differences in the availability of nest-sites due to differences in the distribution of branches. Given random nest placement, the apparent pattern of nest orientation may simply reflect such differential availability of nest-sites while appearing as a significant preference or avoidance. Thus, the spatial nature of environmental cues must be taken into account when interpeting the results of statistical analysis.

In summary, the analysis of circular data can not be approached by calculating simple arithmetic statistics or using commonly prescribed methods of analysis without consideration of hypotheses of expected patterns or any other underlying assumptions. Circular data have distinct statistical properties that require different null hypotheses and distributional assumptions than the linear data with which most ecologists are familiar. Computer simulations have demonstrated that Rao's spacing test is more powerful and robust than any of the compared goodness-of-fit methods especially when analyzing polymodal data. In addition, the nest orientation of Western Kingbirds is probably affected by multiple factors such as microclimate, predation, and habitat structure which make the use of Rao's spacing test indispensable in determining the nature of the pattern of nest orientation.

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