CHARACTERIZING INDEPENDENCE OF OBSERVATIONS IN MOVEMENTS OF COLUMBIAN BLACK-TAILED DEER

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Abstract: Lack of independence in observations of animal locations and movements can cause underestimates of home-range sizes and may lead to inappropriate interpretations of temporal use of space. We used Schoener's Ratio (1981) to assess independence of observations in movements of black-tailed deer (*Odocoileus hemionus columbianus*). We examined the time interval between samples at which independence would occur with, and without, migratory movements, using 12,510 locations from 44 resident and 28 migratory deer. Most datasets contained dependent, or redundant, observations. Even with a 6-week interval between samples (i.e., 8 samples/yr), observations were still dependent for >50% of the deer tested. We found similar results when the data tested represented distance between consecutive locations rather than the locations themselves. In each dataset lacking independence, results were caused by migrations or by infrequent moves to unique places in the home range, both of which made the more common moves comparatively redundant. Such movements skewed data distributions and violated the assumption of normality in the independence test making it difficult to determine a time interval that would compensate for distribution problems. Because most animal location datasets are likely to have skewed data distributions, especially for those animals that migrate, we recommend placing emphasis on sampling animal locations systematically through time rather than trying to determine a time interval that will provide independent location samples. Time intervals between locations should be chosen with the understanding that potential gains in behavioral information are decreased with increasing time intervals between samples.

The problem of temporal dependence of animal locations has been treated by Slade and Swihart (1983), Swihart and Slade (1985*a,b*, 1986), and Swihart et al. (1988). Temporal independence of observations is important to home-range size estimations because most parametric estimators require animal locations to be independent random samples (Ackerman et al. 1990). Home ranges will be consistently underestimated (biased) if based on dependent location observations (Dunn and Gipson 1977, Schoener 1981, Slade and Swihart 1983). Swihart and Slade (1985*b*) documented a strong inverse relationship between estimates of home-range size and the degree of dependence between location observations. Further, because dependent data contain redundant information, less information is available in dependent datasets compared with independent datasets of an equal size (Swihart and Slade 1985*b*). Consequently, dependent data are likely to produce biased estimates even for nonstatistical measures.

The central issue, however, is independence of observations in inferential statistics. Data are independent when the current observation (e.g., position at the current point in time t) is not a function of the last observation (e.g., position at some time interval k previous to the current time t). Alternatively, the variance between consecutive observations is proportional to the overall variance (von Neumann 1941). Consequently, if observations are independent, each observation contributes similarly to the overall estimate of population parameters.

While tests for independence of observations are known for data with 1 dimension (see Box and Jenkins 1976), they are relatively unknown for data with more than 1 dimension such as animal location data (Schoener 1981) that usually are expressed as X and Y spatial coordinates.

A second important distinction of location data is that ordering of the sampled dataset is through a third dimension, time. Location data can, but do not necessarily have to, represent a rate of travel. Additionally, location data can be presented in 1 dimension, an example being the distance between consecutive locations (Fitch 1958). Even though distance between consecutive locations represents only 1 dimension it still is intimately connected to time and is a rate variable. Reynolds and Laundre (1990) found, however, that increases in the time interval between observations leads to poorer information about the true distance traveled during the interval.

Swihart and Slade (1985a) examined Schoener's Ratio statistic (1981) as a potentially useful measurement of independence when observations involve 2 spatial dimensions. Also, Schoener (1981) suggested the ratio may help determine the number of samples necessary for parametric estimation of home-range size. Subsequent to testing Schoener's Ratio, Swihart and Slade (1985a) suggested further uses of the statistic to (1) determine the time interval necessary to obtain independent sample observations, (2) identify shifts or patterns in the use of space, and (3) make comparisons of the rate at which different animals use space.

Since 1985, however, there has been little use of Schoener's Ratio in the manner intended by Swihart and Slade. Holzenbein and Marchinton (1992) used Schoener's Ratio to assess independence of observations of white-tailed deer (*O. virginianus*) locations but presented no documentation of results. They assumed 4 hours, or greater, between observations to be sufficient for a deer to move to any point in its home range. Other researchers demonstrated loss of biological information when using only those animal locations that were judged to be independent by Schoener's Ratio (Reynolds and Laundre 1990). Finally, Kremsater and Bunnell (1992), while recognizing the importance of independence of observations, developed alternative techniques (to Schoener's Ratio) to address specific questions about deer use of landscape mosaics. Kremsater and Bunnell (1992) also argued against testing for independence when location data are to be used for assessing conditional probabilities of decision making.

The lack of use of Schoener's Ratio despite compelling arguments by Swihart and Slade (1985a) prompted us to evaluate independence in our observations of black-tailed deer locations. Our primary interest was the application of Schoener's Ratio when observations included movements of migratory deer. We also wanted to compare assessments of independence between 2 related measures of animal movements: animal locations in space and distance moved between consecutive locations. Our specific objectives were to (1) evaluate independence in observations of black-tailed deer locations, using Schoener's Ratio; (2) assess the influence of migrations on Schoener's Ratio; and (3) evaluate independence in observations of distance between consecutive locations.

METHODS

Deer Location Samples

We obtained location estimates for a sample of radio-collared deer monitored for another study (McNay and Doyle 1990) at 4 sites on Vancouver Island, British Columbia. We used triangulation (White and Garrott 1990) to locate deer with no less than 3 bearings recorded at separate and permanent stations marked at 100-m intervals along roads. Bearings for individual deer location were usually collected in <10 minutes at sites that were line-of-sight with, and close to (<400 m), the transmitter being monitored.

We located deer from January 1982 to June 1984 on an ad hoc schedule that generally resulted in each deer being located once per week. After June 1984 until project completion at June 1991, sampling was standardized so that, during a calendar month, each deer was located at least once per week and once within each quarter of a calendar day. At specific times (usually once/month) we established sessions of comparatively

more intensive monitoring; sampling was increased to once every 2 hours for predetermined periods (usually from 3 to 5 days).

We estimated final deer locations by 2 different techniques. During initial years of study, we plotted triangulation data and determined the location as the centroid of the polygon that resulted from overlapping bearings (Hupp and Ratti 1983). In 1984 and subsequent years, bearing information was retained and analyzed with the maximum likelihood estimator presented by Lenth (1981). We modified a SAS program (SAS Inst. Inc. 1985) by White and Garrott (1990:64) to accept bearings from 3 to 5 sampling stations of known Universal Transverse Mercator grid coordinates. Using the resultant Chi-square goodness-of-fit test for all bearings contributing to each location, and the location's 95% error ellipse size, we made a final judgement on the quality of individual locations a postiori. If the probability of observing poorer goodness-of-fit than that calculated was <0.10, the location estimate was considered poor. We made exceptions when the bearing set was collected for a location close to observer's location (antenna-to-animal distance <100 m). In cases of poor bearing fit, proximity was identified by error ellipses <1 ha. We plotted all locations (Borland Int., Inc. 1992) as a check against field data to identify any recording or coding errors.

Analytical Techniques

We iteratively sampled data to construct 5 individual datasets (Swihart and Slade 1985a). The first 2 datasets were constructed using data collected during intensive monitoring sessions while the last 3 datasets included data collected on a weekly basis. First, we used all data collected during intensive monitoring sessions. Second, we omitted any intensive monitoring data for which the time interval between samples was <4 hours. Third, we omitted data if the time interval between samples was <1 day. Fourth, we disallowed time intervals <17 days, and fifth, time intervals <38 days. In the latter 3 datasets we wanted to obtain average sampling intervals of approximately 1, 3, and 6 weeks, respectively. Henceforth, we will refer to these datasets as 2 hour, 4 hour, weekly, 3 week, and 6 week.

We calculated Schoener's Ratio (Schoener 1981) for each deer-session (2- and 4-hour datasets) and for each deer (weekly, 3-, and 6-week datasets). We calculated the critical value of Schoener's Ratio using methods suggested by Swihart and Slade (1985a,b) to test the null hypothesis that deer locations were independent. We chose $\alpha = 0.25$ (Swihart and Slade 1986) unless stated otherwise.

We used 2 methods to examine the influence of migrations using the weekly, 3-, and 6-week datasets. First, to identify the effect that each location had on the overall statistic, we recalculated Schoener's Ratio each time a new location was added to the dataset. Second, we omitted migratory movements and calculated Schoener's Ratio for each spatially exclusive, seasonal home range. We determined migratory movements by visual inspection of chronological location plots for each deer. Inspection of each movement enabled us to identify those composing regular trips with predictable return moves (Sinclair 1984).

To examine independence of distances between consecutive locations, we measured the straight-line distance from the last location to the current location. We first looked for indications that data reflected a rate of travel by plotting distance between consecutive locations against time between consecutive locations and by testing for linear trends using correlation analysis (SAS Inst. Inc. 1985). Secondly, we used the mean square successive difference test, alternatively known as the V-statistic (von Neumann et al. 1941), to evaluate independence in observations.

RESULTS

We monitored 44 resident and 28 migratory deer for 253 deer-years and 12,510 locations. We sampled 42 of those deer during 24 intensive monitoring sessions for a total of 133 deer-sessions. Not all deer were sampled during each intensive monitoring session. Intensive monitoring accounted for 4,039 of the locations. Complete bearing information was available for 9,234 of the locations, and with those data we calculated goodness-of-fit and error ellipse sizes for each location estimate. Two percent of the locations were generated from bearings with poor goodness-of-fit (χ^2, $P \leq 0.10$) and large error ellipses (>1.0 ha). Generally, locations had a 95% error ellipse of <1 ha ($\bar{x} = 0.98$ ha, SD = 6.5, $n = 12,103$).

The average time interval between samples was 2.0 hours (SD = 1.6, $n = 3,905$) in the 2-hour dataset, and 5.4 hours (SD = 2.2, $n = 1,613$) in the 4-hour dataset. Time intervals between less

Table 1. Percentage of total or seasonal black-tailed deer ranges where the hypothesis of independence[a] of location observations was not rejected. Values in parentheses are the number of seasonal or total home ranges tested from data collected during 1982–91 on Vancouver Island, British Columbia.

Range type	Deer behavior	% independent ranges in time interval				
		2 hour	4 hour	Weekly	3 week	6 week
Ratio test						
Total	Resident	7 (71)	4 (70)	9 (44)	27 (44)	41 (44)
Total	Migratory	6 (62)	10 (61)	0 (28)	7 (28)	18 (28)
Seasonal	Migratory			21 (56)	54 (48)	49 (41)
V test						
Total	Resident	45 (71)	61 (70)	7 (44)	43 (44)	54 (44)
Total	Migratory	42 (62)	82 (61)	25 (28)	57 (28)	68 (28)
Seasonal	Migratory			34 (56)	50 (48)	56 (41)

[a] Two tests were used: (1) Schoener's ratio (Schoener 1981) tests independence of observations in 2-dimensional space, and (2) von Neumann's V (von Neumann et al. 1941) tests independence of observations of distances between consecutive locations.

intensive samples were 8.1 days (SD = 10.3, n = 8,464) in the weekly dataset, 24.6 days (SD = 14.2, n = 2,865) in the 3-week dataset, and 46.4 days (SD = 16.9, n = 1,506) in the 6-week dataset.

Independence of Location Observations

The hypothesis of independence was rejected ($P < 0.25$) for most deer location datasets regardless of the time interval between locations (Table 1), especially for deer that migrated. With a 1-week time interval between locations, none of the datasets for migratory deer were independent, but 10 and 18% of the datasets were independent at the 4-hour and 6-week intervals, respectively. The highest percentage of independent datasets (41% or 18 of 44 deer) came from resident deer with 6 weeks between location samples.

Effect of Migrations on Independence of Location Observations

Migratory movements affected Schoener's Ratio. The first occurrence of a migration in each dataset caused Schoener's Ratio to drop indicating lack of independence. Subsequent migrations, however, were largely undetectable (Fig. 1). Migrations were not the only movements that led to rejection of independence although they were the most conspicuous. Datasets for resident deer (or for migratory deer within a seasonal range) also became dependent if the deer moved to a unique place at the periphery of its range. Alternatively, in cases where no migrations or outlier locations were recorded, results of Schoener's Ratio tests often oscillated between independence and dependence in an unpredictable pattern (Fig. 2). Only 5 of 345 tests revealed datasets that were judged independent through the data collection period.

When we removed migratory movements and recalculated Schoener's Ratio from spatially dis-
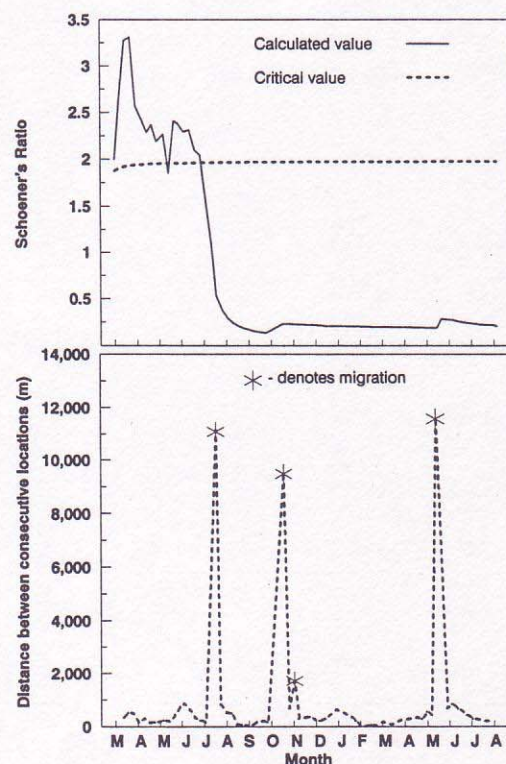

Fig. 1. A chronological plot of Schoener's Ratio (1981) calculations (top) and distance between consecutive locations (bottom) from location observations collected weekly during 1982–91 on a radio-collared black-tailed deer (#NRC13402) at Nanaimo River, Vancouver Island, British Columbia. Critical value is the Schoener's Ratio test statistic.
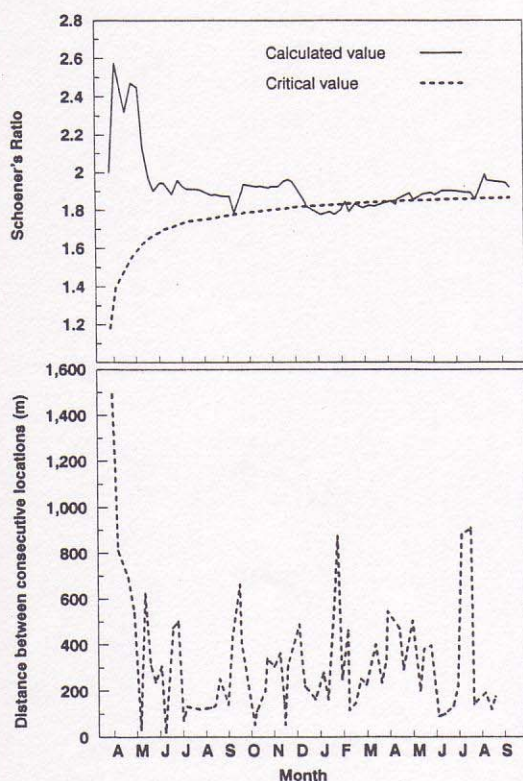
Fig. 2. A chronological plot of Schoener's Ratio (1981) calculations (top) and distance between consecutive locations (bottom) from location observations collected weekly during 1982–91 on a radio-collared black-tailed deer (#NIM12901) at Nimpkish River, Vancouver Island, British Columbia. Critical value is the Schoener's Ratio test statistic.

tinct seasonal ranges the independence statistic improved (Table 1). In >50% of the seasonal range datasets (26 of 48 seasonal ranges), we did not reject ($P > 0.25$) independence of location observations when the time interval between observations was 3 weeks (Table 1).

Independence of Distance Between Consecutive Locations

Distance between consecutive locations was poorly associated with time between those locations ($r = 0.26$, $P < 0.001$, $n = 12,437$). At most time intervals, except the shortest (intensive monitoring), deer traveled a range of distances from 0 to 14 km (Fig. 3).

Von Neumann's V indicated more consistent independence among observations of distances than was achieved among spatial locations (Table 1). We did not reject ($P > 0.25$) independence in 82% of the intensive monitoring sessions recorded for migratory deer, using 4 hours

between locations (50 of 61 deer-sessions). The weekly dataset showed the poorest percentage of independent datasets (7–34%). There was no improvement in going from a 3-week to a 6-week time interval nor did eliminating migrations improve independence of data collected on migratory deer (Table 1).

DISCUSSION

Most of our datasets on black-tailed deer were composed of statistically dependent observations (Table 1). If our objectives were to measure the amount of space used by deer, or the average distance traveled by deer, we would conclude that our estimates would likely be biased low (Schoener 1981, Swihart and Slade 1985b). The bias would be the result of the sample containing redundant observations.

Migrations led to dependence in datasets for migratory black-tailed deer because they indicated relatively infrequent moves to different sites. Such movements expanded the overall variance in one, or both, spatial coordinates and hence, daily use of sites within a seasonal range became comparatively redundant once a migration was made. In this respect, Schoener's Ratio performed well as a measure of a significant, first-time change in the use of space. Because the statistic is calculated from average deviations, however, subsequent changes in use of space went undetected (Fig. 1).

Although our observations of distance between consecutive locations had marginally less dependence, we found results similar to those in our investigation of how deer use 2-dimensional space. Again, in ≥50% of the cases, black-tailed deer infrequently made larger than normal moves, most of which were migrations. Those large distance movements effectively caused the more common movements (generally <250 m) to become comparatively redundant.

The conclusion of dependence in both of the above cases, however, is based on a little mentioned, yet important, assumption of the 2 analytical techniques. Both tests require normal data distributions because they are calculated from average deviation of the samples (von Neumann 1941, Schoener 1981). Application of the tests in circumstances of skewed data distributions could lead to an apparent lack of independence even when independence is achieved. Swihart and Slade (1985a,b) were careful to ensure their constructed datasets came
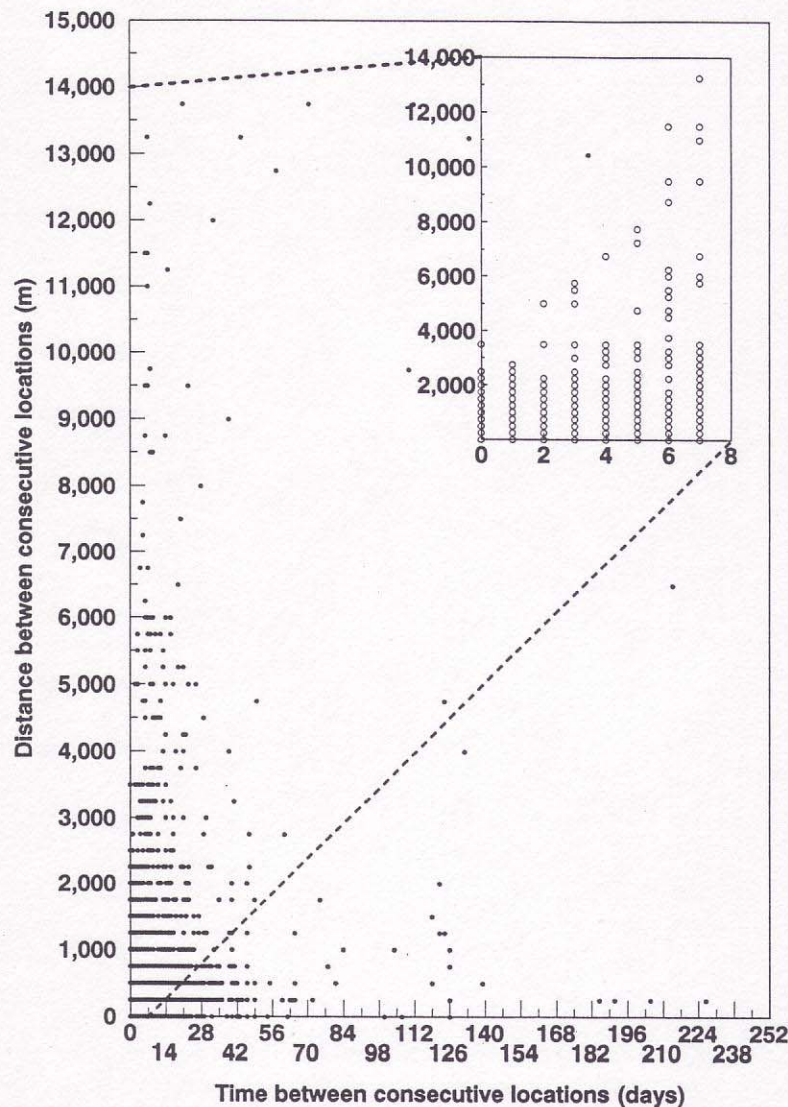
Fig. 3.   Scatter plot of distance (m) and time (days) between consecutive observations of individual, radio-collared black-tailed deer location estimates observed during 1982–91 on Vancouver Island, British Columbia. Inset shows detail of the relationship at lower axis positions. Location estimates were derived by maximum likelihood estimation (Lenth 1981) and distance was the straight-line distance.

from a normal distribution. When they dealt with data collected from real observations, Swihart et al. (1988) dropped, from their calculations, any dataset where the animal shifted its activity center. Swihart and Slade (1985*b*) alluded to this effect of migrations by indicating that temporal rhythmicity in movements may reduce likelihood of independence. We concur, noting that the temporal rhythmicity would lead to nonnormality and hence an apparent lack of independence.

Normality of location data is influenced by temporal use of space (or distance traveled). If distance traveled in space was always linear with time, then distance measurements at specific time intervals would tend to be normally distributed. Movements, however, are the essence of behavior and animals may choose to move at a variety of rates from running to no movement at all. Movements are unlikely to ever be normally distributed. Lack of normality in our data was most conspicuously caused by migrations

that could occur within the time interval between most location sampling (Fig. 3). In fact, with the exception of location sampling during intensive monitoring, deer had time to travel anywhere in their home ranges (i.e., our distance measurements were not likely to be indicative of any specific rate of travel). We concluded that because behavior contributed to the lack of a normal distribution in location observations, it impaired our ability to find an appropriate sampling interval for black-tailed deer and led to an apparent dependency in the data. Had all our data been more indicative of a rate of travel (e.g., the 2- and 4-hour datasets; Fig. 3, inset) the arbitrary culling of data (see Methods) should have produced better tests of independence and likely less dependence between samples.

MANAGEMENT IMPLICATIONS

We concluded that testing our location data for independence employed techniques that were not robust to skewed data distributions that can be caused by migrations between seasonal ranges. To avoid apparent dependence of observations, we would have had to disregard about 90% of our data to end up with an average of 8 locations/deer-year. Doing so would have resulted in sample sizes below that required for many analyses and would have eliminated information about the dynamic manner in which black-tailed deer use space.

In an operational sense, the primary concern about independence should focus on whether an animal has had time to move to any location within its home range before the next observation is taken (Lair 1987). That was the interpretation adopted by Holzenbein and Marchinton (1992) when they chose a sampling interval of 4 hours for their observations of white-tailed deer. White and Garrott (1990:148) expanded on that principle by suggesting the real issue was to properly sample the time interval over which an estimate is to apply. A systematic sample over specific time periods eliminates the effects of bias due to redundant data (White and Garrott 1990:148) but still inflates sample size causing variance to be underestimated. Biased variance, however, would be of little concern in home-range estimates because it is never calculated for a single home range.

Furthermore, choosing appropriate time intervals to sample animal locations appears to be more a problem of study objectives than of statistical independence, provided samples are obtained systematically. Lair (1987) observed that minimum time intervals to statistical independence can be long enough to preclude investigations of home-range characteristics. While samples taken close together in time may be redundant statistically, they reveal comparatively better behavioral information on use of space than samples taken farther apart in time (Lair 1987, Reynolds and Laundre 1990). In this study, black-tailed deer were observed to travel even the largest distances in less time than our sampling intervals in all but the intensive monitoring (Fig. 3). For that reason we concluded that our weekly observations were likely to have biological independence (Lair 1987) even though they may be declared statistically dependent by the tests we used. We regarded the datasets to have apparent dependence rather than actual dependence because the data violated the assumption of normality required for independence tests.

We recommend that investigators strive to achieve biological independence in systematic observations of animal movements rather than passing the criteria of statistical tests that assume normality. Data distributions of animal movements will rarely follow a normal distribution because movements reflect behavioral decisions. Any test of independence using the nonnormal data would likely lead to conclusions of apparent redundancy forcing elimination of important biological information. Our suggestions imply that investigators assume spatial and temporal dependence, rather than independence, in animal location data. Making that admission could help advance traditional data analysis (Tukey 1977) beyond exploratory techniques to those that acknowledge and model statistical dependence (Houston et al. 1988, Rossi et al. 1992).

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