Method and precision in estimation of dolphin school size with vertical aerial photography

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Abstract.–Field and laboratory procedures were used to acquire dolphin school size estimates from vertical aerial photographs. Multiple photographs were taken of 48 separate schools during a 1989 eastern tropical Pacific (ETP) dolphin abundance survey. During a 12-week "counting period," three readers did independent counts of dolphins in the photographs. For each school, the best photograph imagery was selected and the mean of the three independent counts was used to estimate its "true" size. The coefficient of variation (CV) for school size estimates (between-reader precision) averaged 5.4% and ranged between 1.2% and 14.6%. Most (92%) of the schools were estimated with precision, resulting in a CV of less than 9.0%. Within-reader CV averaged 3.5% and ranged 1.4%–7.1%, indicating that readers were quite precise. To test if reader methods were constant during the counting period, temporal trends in estimates were tested by linear regression analyses and a repeated-counts experiment with repeated measures analysis of variance (RM-ANOVA). Regression analyses indicated no significant temporal trends or bias in the deviation of counts from the means. The RM-ANOVA showed a significant "reader with time" interaction which was attributed to the relatively high variability between readers in counts made at the start of the experiment. Results suggested that methods were constant and counts were precise after an initial "warm-up" counting session.

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Visual estimation of the number of dolphins in a school is difficult because dolphins dive and the entire school is rarely visible at the sea surface at one time. Shipboard observer estimates can be highly variable and they may be biased (Scott et al., 1985; Anganuzzi and Buckland, 1989). Consequently, estimates of dolphin population abundance derived from visual survey data may be biased, and resulting management decisions aimed at conserving these populations may be inappropriate.

The Southwest Fisheries Science Center (SWFSC) has been conducting surveys to monitor temporal trends in the abundance of eastern tropical Pacific (ETP) populations of the pantropical spotted dolphin (*Stenella attenuata*), spinner dolphin (*S. longirostris*), striped dolphin (*S. coeruleoalba*) and common dolphin (*Delphinus delphis*). These surveys are one part of a multifaceted effort to conserve ETP dolphins subjected to incidental mortality in the international purse-seine fishery for yellowfin tuna, *Thunnus albacares* (Perrin, 1975; Wade and Gerrodette, 1992). Starting in 1987, in response to the problem of potential bias in visual school-size estimates, annual ETP surveys were complemented with aerial photography of dolphin schools. This allowed shipboard-observer estimates to be compared with estimates (of the same schools) taken from counts of dolphins in the photographs.

School size estimates derived from large-format (126-mm) aerial photographs were validated during a 1979 study when five separate schools (size range: 161–396 dolphins) were photographed and then captured in a tuna purse-seine net (Scott et al., 1985). Results showed that dolphin counts from the photographs were not statistically different from counts tallied by hand as dolphins were being released from the net. This suggested that counts from aerial photographs approximated "true" school size.

This report details photographic and counting methods used to derive dolphin[1] school size estimates from large-format vertical aerial photographs. Many of the techniques originated with Scott et al. (1985). The techniques were modified to support the photography and laboratory efforts associated with large-scale ETP dolphin population surveys (i.e., annual surveys of 120 days; covering a 19-million-km^2 study area). After a survey in 1989, three readers did independent dolphin counts from approximately 200 dolphin school photographs (multiple photographs were taken for 48 separate schools) over 12 consecutive weeks. For each school, the best photograph imagery was selected (according to criteria described below) and the mean of the three independent counts was used to estimate its true size. The coefficient of variation (CV) was used to characterize the precision (between-

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[1] For purposes of this paper, "dolphin" refers to dolphins as well as small toothed-whales that are included in the photograph sample.

and within-reader) associated with the school size estimates.

One concern was that during the 12-week "counting period," readers might be inconsistent in the application of criteria (cognitive or physical methods, or both) used for counting. If readers were inconsistent, then this might affect the accuracy and precision of the estimates. A two-step approach was taken to address this concern. First, temporal trends in the deviation of counts from the means (see Sokal and Rohlf, 1981, p. 50) were evaluated by linear regression. This approach assumed that the mean of three reader counts was close to the true school size and that the sample error was normally distributed. If individual reader counts were not normally distributed, then this might indicate reader bias or a change in criteria. Second, readers did repeated-counts (at four time points during the counting period) of a known sample of photographed schools. This was done to evaluate the consistency of individual readers (within-reader precision) and to test the hypothesis that dolphin counts (from the same photographs) done at the beginning, middle, and end of the counting period were independent of temporal effects. If the hypothesis proved true, then this would support the idea that counting criteria were constant throughout the counting period.

Materials and methods

At sea

Aerial photographs analyzed in this report were taken with Chicago Aerial Industries KA-62 aerial cameras mounted vertically on a Hughes 500-D helicopter. The helicopter was stationed aboard the National Oceanic and Atmospheric Administration (NOAA) survey ship *David Starr Jordan*. All cameras had forward-motion compensation (to minimize photo image blur from aircraft movement) and a 76.2-mm lens. Large-format (126-mm) Kodak Aerochrome MS 2448 color film was used. In order to minimize the behavioral response (scattering and deep diving) of the dolphin schools to the helicopter, photographs were taken at 244 m (800 ft) altitude. The scale of the photographs at this altitude was 1:3200, the sea surface area in a photograph frame was 366 m^2, and a 2-m dolphin measured 0.63 mm on the film. The camera cycle rate was programmed to expose for approximately 80% film image overlap, i.e., 80% of the area photographed in one frame was photographed again in the next successive frame. Successive exposed photograph frames for a school were recorded as a complete "photo-pass." To enhance the probability of photographing an entire school, multiple photo-passes (avg.=5) were made over a school.

In the laboratory

Counts Light tables equipped with dissection microscopes (0.7× to 7× variable objective and 10× widefield oculars) were used to view and count the dolphin images during counting. Dolphins were counted by hand-tally while being plotted with a permanent marker on a clear acetate overlay. The marked overlay, when moved to the image overlap area of adjacent frames and aligned over dolphins that were previously plotted, made it easier to identify those dolphins not yet counted in the photo-pass. The photo-pass was the unit on which school size estimates were based (Scott et al, 1985); each pass was counted independently by three readers.

Criteria for selecting the "true" school size For each of the 48 photographed schools, the readers chose (by group consensus) the one photo-pass where the mean of the reader counts was the best estimate of true school size. This decision was based on the precision of the three replicate counts and the reader assigned "quality ratings" for the photo-pass. Ratings reflected how confident the reader was in the accuracy of the count. For each photo-pass, readers independently assigned quality ratings ranging from 1 to 4. A rating of "1" indicated that a photo-pass had "excellent" quality. A rating of "2" indicated that the count was "good" despite the presence of some questionable images (i.e., it was difficult to discern and count dolphins accurately when images were partially obscured by light-glare or when photographic resolution was reduced for deep swimming dolphins because of loss of light with sea depth). A photo-pass was rated "3" or "fair" when more questionable images were encountered, but readers still believed the count was a close approximation of true school size. A photo-pass rated "4" was deemed unusable for size estimation because the reader felt there were too many questionable images and the count was not a reliable estimate of true school size.

One source of between-reader variation in dolphin photograph counts was reader error, where dolphins were missed or counted twice. Variation also occurred because readers differed in their interpretations of whether questionable images were dolphins or merely background water turbulence in the photographs. Based on the premise that "precision leads to accuracy" (Sokal and Rohlf, 1981), for each photo-pass, the CV of the three independent counts was used to monitor the reliability of the school size estimate. For photo-passes where the CV of the counts exceeded 10%, the dolphin school was re-counted (independently) to see if the precision of the estimate could be improved. If the CV was above 15% after a second count, the photo-pass was excluded from the study because the counts were considered too variable and little confidence was placed in the accuracy of the estimate.

Analytical methods The CV was plotted against the variables "school size" and "quality rating" to evaluate how different school sizes and photograph image qualities affected precision. The CV was also used to characterize the precision of individual readers in repeated-counts as described below.

The percent deviation (PD) is a measure of how distant (+ or −) a count is from the mean. Because this difference is expressed as a percentage of the mean, the PD is a consistent index of deviation relative to changes in the mean. For the PD, let x_{ij} be the ith reader's determination of the size of school j. The average determination (or mean) over three readers of the size of the jth school was given by

$$\bar{x}_{.j} = \frac{1}{3}\sum_{i=1}^{3} x_{ij} \ . \qquad (1)$$

The PD of x_{ij} is expressed as

$$PD_{ij} = \frac{x_{ij} - \bar{x}_{.j}}{\bar{x}_{.j}} * 100 \ . \qquad (2)$$

PD values were plotted to evaluate whether individual reader counts were normally distributed or readers were biased (i.e., tended to count high or low relative to the mean). To test for temporal trends in individual reader counts, PD values were regressed against the variable "time." Time represented the chronological sequence, unique for each reader, in which the 48 schools were counted. Logistically, it was impractical for readers to follow the same sequence in working with the photo-passes.

For the repeated-counts experiment, a known sample of six photographed dolphin schools (henceforth referred to as the "experiment schools"), which varied in school size and image quality, were counted four times. Counts were done once at the start of the counting period, then again every 25 days during the period. Changes with time (temporal trends) due to the variables of "school size," "image quality," and "reader" were tested by using a repeated measures analysis of variance (RM-ANOVA) model from Winer (1971; p. 337).[2] Outlier counts were identified by using Shapiro-Wilk's test for normality at $\alpha = 0.05$ (Shapiro and Wilk, 1965). After log-transformation, data met F-test requirements of homoscedasticity according to Levene's test at $\alpha = 0.05$ (computer program BMDP7D used, Dixon et al. 1988). The RM-ANOVA was computed using the software program SuperANOVA (Abacus Concepts, 1990).

Results and discussion

Scott et al. (1985) reported that dolphin school size estimates derived from aerial photographs were accurate and more precise than visual estimates. They found the standard deviation of estimates (log-transformed) averaged 6% of school size for photographic estimates and 10%–30% of school size for visual estimates. The CV for estimates (untransformed) of the 11 schools used in their precision analysis averaged 8.4% (range: 3.7%–15.1%) indicating slightly less precision when compared with estimates presented here (avg. CV: 5.4%; range: 1.2%–14.6%; Table 1). The difference is explained, in part, by their statistical model, which accounted for variance due not only to independent repetitive counts (2 to 4 per photo-pass), but also due to camera types (126- and 229-mm formats) and multiple photo-passes (2 to 7) for a given school. In the present study, variability was minimized by use of one type of camera (126-mm format) and by including only counts of the single best photo-pass for a school.

School size estimates averaged 146 and ranged between 4 and 633 (Table 1). Most schools (92%) were estimated with precision that resulted in a CV of less than 9.0%, and precision varied little with school size (Fig. 1 and Table 2). Estimate precision tended to decrease with decreased quality of the dolphin school photographs (Fig. 2). PD values (listed in Table 1) plotted for individual readers appeared normally distributed, indicating no between-reader bias in counts of the dolphin images.

Repeated-count data are presented in Table 3. Outlier values for experiment school number III (Table 3) resulted from reader error when dolphins were missed as the marked acetate was moved from the dolphin low density area of the photo-pass (in this case, the beginning of the photo-pass) to the high density area. Alternatively, when dolphins in the high density area were counted first, the precision of the estimate was improved because the majority of dolphins in the school were plotted and counted at the onset; this made it easier to track individual dolphins on adjoining frames.

Within-reader CV for repeated counts averaged 3.5%. Reader 2, the most experienced reader, was most precise in repeated counts (avg. CV: 2.6%; range: 1.4–3.8%) followed by reader 3 (avg. CV: 3.4%, range: 1.5–5.1%), and Reader 1 (avg. CV: 4.7%, range: 2.5–7.1%). The RM-ANOVA showed significant differences between

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[2] Model detailed in: Gilpatrick, J. W. Jr. (1992). Using vertical aerial photographs to estimate dolphin school sizes: precision and consistency. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Southwest Fish. Sci. Cent., P.O. Box 271, La Jolla, CA 92038. Admin. Rep. LJ-92-35, 20 p.

Table 1

Counts, mean school size, CV, average quality ratings, and PD values for schools photographed in the 1989 ETP dolphin population survey.

		Reader counts[2]						Reader PD[4]		
School no.	Species codes[1]	R1	R2	R3	Mean school size	CV (%)	Avg. quality rating[3]	R1	R2	R3
1	S.COE	37	35	39	37.0	5.4	1.3	0.0	–5.4	+5.4
2	S.ATT	250	227	221	232.7	6.6	2.7	+7.5	–2.4	–5.0
3	S.LON	153	139	147	146.3	4.8	1.0	+4.6	–5.0	+0.5
4	S.COE	57	54	56	55.7	2.7	2.3	+2.4	–2.9	+0.6
5	S.ATT/S.LON	124	127	130	127.0	2.4	2.3	–2.4	0.0	+2.4
6	S.ATT/S.LON	192	196	216	201.3	6.4	1.7	–4.6	–2.7	+7.3
7	S.ATT/S.LON	274	236	242	250.7	8.2	1.0	+9.3	–5.9	–3.5
8	S.COE	48	47	49	48.0	2.1	1.0	0.0	–2.1	+2.1
9	F.ATT	17	18	18	17.7	3.3	1.0	–3.8	+1.9	+1.9
10	S.ATT/S.LON	81	78	77	78.7	2.7	1.0	+2.9	–0.9	–2.1
11	S.ATT/S.LON	412	416	398	408.7	2.3	1.3	+0.8	+1.8	–2.6
12	S.ATT/S.LON	101	106	118	108.3	8.1	2.3	–6.8	–2.2	+8.9
13	S.LON	20	20	21	20.3	2.8	2.7	–1.6	–1.7	+3.3
14	S.ATT/S.LON	107	113	113	111.0	3.1	1.3	–3.6	+1.8	+1.8
15	S.ATT	118	124	109	117.0	6.5	1.3	+0.9	+5.9	–6.8
16	S.ATT/S.LON	618	607	675	633.3	5.8	2.0	–2.4	–4.2	+6.6
17	P.ELE	400	391	399	396.7	1.2	1.0	+0.8	–1.4	+0.6
18	S.COE	58	53	60	57.0	6.3	1.3	+1.8	–7.0	+5.3
19	S.COE	52	55	61	56.0	8.2	1.7	–7.1	–1.8	+8.9
20	D.DEL	317	323	326	322.0	1.4	1.0	–1.6	+0.3	+1.2
21	D.DEL	326	312	367	335.0	8.5	1.3	–2.7	–6.9	+9.6
22	S.COE	24	23	25	24.0	4.2	1.3	0.0	–4.2	+4.2
23	G.MAC	19	18	19	18.7	3.1	1.0	+1.8	–3.6	+1.8
24	S.COE	75	77	68	73.3	6.4	2.0	+2.3	+5.0	–7.3
25	S.COE	34	30	32	32.0	6.3	1.3	+6.3	–6.3	0.0
26	S.COE	166	171	181	172.7	4.4	1.7	–3.9	–0.9	+4.8
27	D.DEL	66	64	60	63.3	4.8	1.7	+4.2	+1.1	–5.3
28	S.ATT/S.LON	216	216	233	221.7	4.4	1.3	–2.6	–2.6	+5.1
29	S.ATT	25	24	23	24.0	4.2	1.0	+4.2	0.0	–4.2
30	G.GRI	56	64	55	58.3	8.5	1.3	–4.0	+9.7	–5.7
31	S.BRE	4	4	5	4.3	13.3	2.0	–7.7	–7.7	+15.4
32	S.LON	576	678	548	600.7	11.4	2.3	–4.1	+12.9	–8.8
33	S.ATT	38	50	49	45.7	14.6	2.7	–16.8	+9.5	+7.3
34	S.COE	40	39	40	39.7	1.5	1.0	+0.8	–1.7	+0.8
35	S.ATT	88	90	80	86.0	6.2	1.7	+2.3	+4.7	–6.7
36	S.LON	315	324	350	329.7	5.5	1.3	–4.5	–1.7	+6.2
37	S.COE	26	25	24	25.0	4.0	2.0	+4.0	0.0	–4.0
38	S.COE	150	147	156	151.0	3.0	2.0	–0.7	–2.7	+3.3
39	S.BRE	36	34	35	35.0	2.9	1.0	+2.9	–2.9	0.0
40	S.ATT/T.TRU	284	293	337	304.7	9.3	2.3	–6.8	–3.8	+10.6
41	G.GRI	20	19	18	19.0	5.3	1.0	+5.3	0.0	–5.3
42	S.COE	35	34	35	34.7	1.7	1.0	+1.0	–1.9	+1.0
43	S.COE	73	74	88	78.3	10.7	2.0	–6.8	–5.5	+12.3
44	S.COE	154	154	144	150.7	3.8	1.3	+2.2	+2.2	–4.4
45	D.DEL	450	526	474	483.3	8.0	1.3	–6.9	+8.8	–1.9
46	S.COE	80	87	92	86.3	7.0	1.7	–7.3	+0.8	+6.6
47	S.COE	23	24	23	23.3	2.5	1.3	–1.4	+2.9	–1.3
48	S.COE	39	39	37	38.3	3.0	2.0	+1.7	+1.7	–3.7
Average:		145.5	145.9	147.4	145.5	5.4	1.6			

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[1] Species codes: S.COE = *Stenella coeruleoalba*; S.ATT = *S. attenuata*; S.LON = *S. longirostris*; F.ATT = *Feresa attenuata*; P.ELE = *Peponocephala electra*; G.MAC = *Globicephala macrorhynchus*; D.DEL = *Delphinus delphis*; G.GRI = *Grampus griseus*; S.BRE = *Steno bredanensis*; T.TRU = *Tursiops truncatus*. Multiple species codes indicate mixed-species schools.

[2] Reader codes: R1 = Reader 1; R2 = Reader 2; R3 = Reader 3.

[3] Obtained by averaging the three independent reader assigned quality ratings.

[4] PD = percent deviation of reader count from the mean.

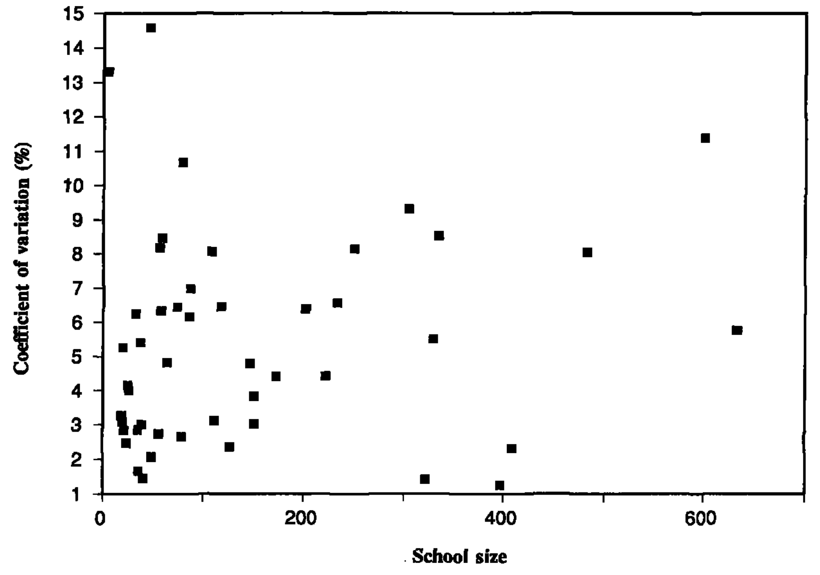

Figure 1

Comparison of mean school size and precision (using CV) of count estimates for schools (n=48) photographed during the 1989 ETP dolphin population survey.

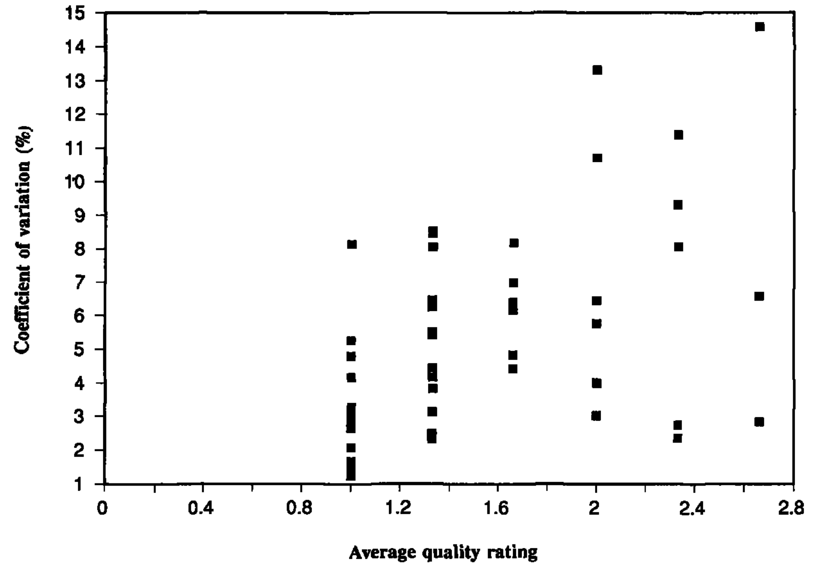

Figure 2

Relationship between photograph quality ratings (averaged for three independent readers) and precision (using CV) of count estimates for schools (n=48) photographed during the 1989 ETP dolphin population survey.

levels of the factors "school size" and "quality rating" (see between-factors; Table 4). This was expected because photographed schools of different sizes were intentionally selected for the analysis. Often, with RM-ANOVA, between-factor effects are confounded with different levels of the factors (as is true for the two factors above) and it is the temporal trends of the within-factor data that are of primary interest in the analysis (Winer, 1971, p. 299). There were no differences between readers in the overall means of their repeated counts (temporal trends not considered; P=0.7898; Table 4).

Table 2

Comparison of precision of estimates for small (<125 dolphins), medium (125–350 dolphins), and large (>350 dolphins) schools.

	CV (%)	
School size	Mean	Range
Small	5.3	(1.5–14.6)
Medium	5.2	(1.4–9.3)
Large	5.7	(1.2–11.4)
overall mean:	5.4	
overall range:		(1.2–14.6)

The F value for the within factor "Time" indicated no significant linear trend for repeated-counts (with the mean of the three reader counts). However, a significant interaction for "reader with time" (F=3.503; P=0.0258; df=6, 31) indicated there were differences between readers in the respective temporal trends of their repeated-counts (Fig. 3). To investigate the source of the significant effect, the trend data for each reader were tested *a posteriori* by contrasts among means with linear coefficients to weigh the log-transformed data (Sokal and Rohlf, 1981; Abacus Concepts, 1990). Results showed the mean of Reader 1's counts at time one differed significantly from the means of counts made at times two, three, and four (F=14.977; P=0.0005; df=1). This suggested that Reader 1's counts made at time one were important in causing the significant "reader with time" interaction.

Because the initial counts (at time one) of the experiment schools were done just prior to the start of the 12-week counting period, this suggested that

Table 3

Repeated counts experiment. Counts of the experiment schools were done at the start of the 12-week counting period, then repeated every 25 days during the period. Observations in parentheses are outlier values.

				Time			
Schools	School size	Quality rating	Reader	Time 1	Time 2	Time 3	Time 4
I	Small	Excellent	1	64	64	66	67
			2	69	66	68	70
			3	61	65	64	69
II	Small	Good	1	34	38	38	35
			2	36	35	36	36
			3	38	39	39	38
III	Medium	Excellent	1	(191)	242	230	236
			2	232	252	236	243
			3	(189)	(193)	(205)	(206)
IV	Medium	Good	1	(169)	214	194	203
			2	207	211	209	206
			3	213	195	194	205
V	Large	Excellent	1	401	468	468	450
			2	457	450	429	432
			3	440	451	429	467
VI	Large	Excellent	1	464	516	525	490
			2	541	527	534	496
			3	507	519	534	527

Table 4

Results from repeated measures analysis of variance (RM-ANOVA).

	df	Sum of squares	Mean square	*F*-value	*P*-value	G.-G.[1] *P*-value
School size	2	8.880	4.4400000	431.485	0.0001	
Quality rating	1	0.290	0.2900000	28.145	0.0003	
Reader	2	0.005	0.0020000	0.241	0.7898	
Error (between factors)	11	0.113	0.0100000			
Time	3	0.002	0.0010000	2.504	0.0775	0.0855
Time * school size	6	0.002	0.0003323	1.653	0.1661	0.2365
Time * quality rating	3	0.001	0.0003299	1.641	0.2001	0.1883
Time * reader	6	0.004	0.0010000	3.503	0.0092	0.0258
Error (within factors)	31	0.006	0.0002011			

[1] *P*-value corresponding to degrees of freedom adjustment using the Greenhouse-Geisser (1959) epsilon factor (=0.692) to correct for correlation of repeated measures. See Anderson (1958); Barcikowski and Robey (1984); Dunn and Clark (1987).

between-reader variance may have been atypically high early in the counting period as well. The regression analyses of PD values with time, however, did not provide strong evidence for this because reader counts were close to the mean values and no significant temporal trends were detected (Fig. 4). Probable cause for the significant effect was that readers were "out of practice" at the start, especially Reader 1. Prior to the

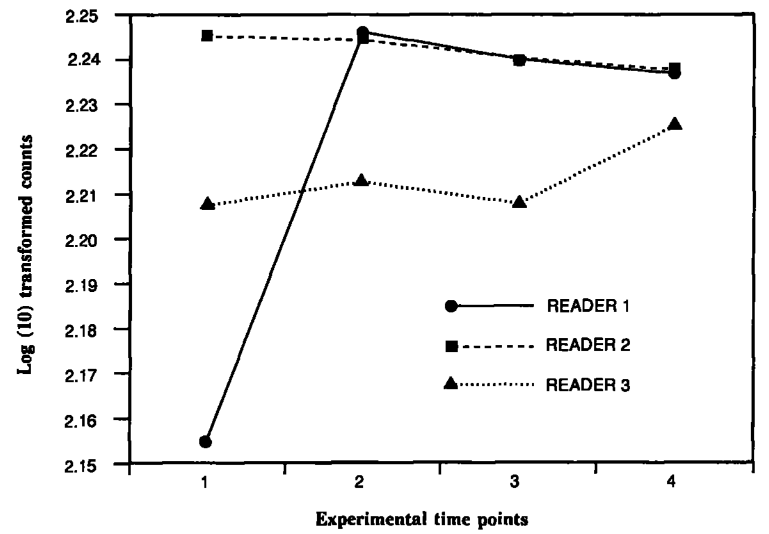

Figure 3

Temporal profiles of the means for counts (log-transformed) made by three independent readers during the repeated-counts experiment.

1991 counting period, a "warm-up" counting session was effective in improving estimate precision, i.e, between-reader CV went from an average of 8% to 4% within one day.

Conclusion

Results suggest that after a prolonged absence from interpreting dolphin school photographs and doing counts, a warm-up session, where readers are refreshed in counting technique, is important for minimizing reader error and improving precision. Estimate precision is also improved when plotting and counting is initiated at the dolphin high-density area in a photopass. The field and laboratory methods described in this report proved reliable in providing precise dolphin school-size estimates for population abundance studies. The CV statistic and PD index will be used for inter- and intra-annual quality control of dolphin school estimates taken from aerial photographs. The analytical methods used in this paper to describe precision and consistency are applicable to other fisheries and terrestrial wildlife research efforts where independent repetitive counts are conducted for parameter estimation.

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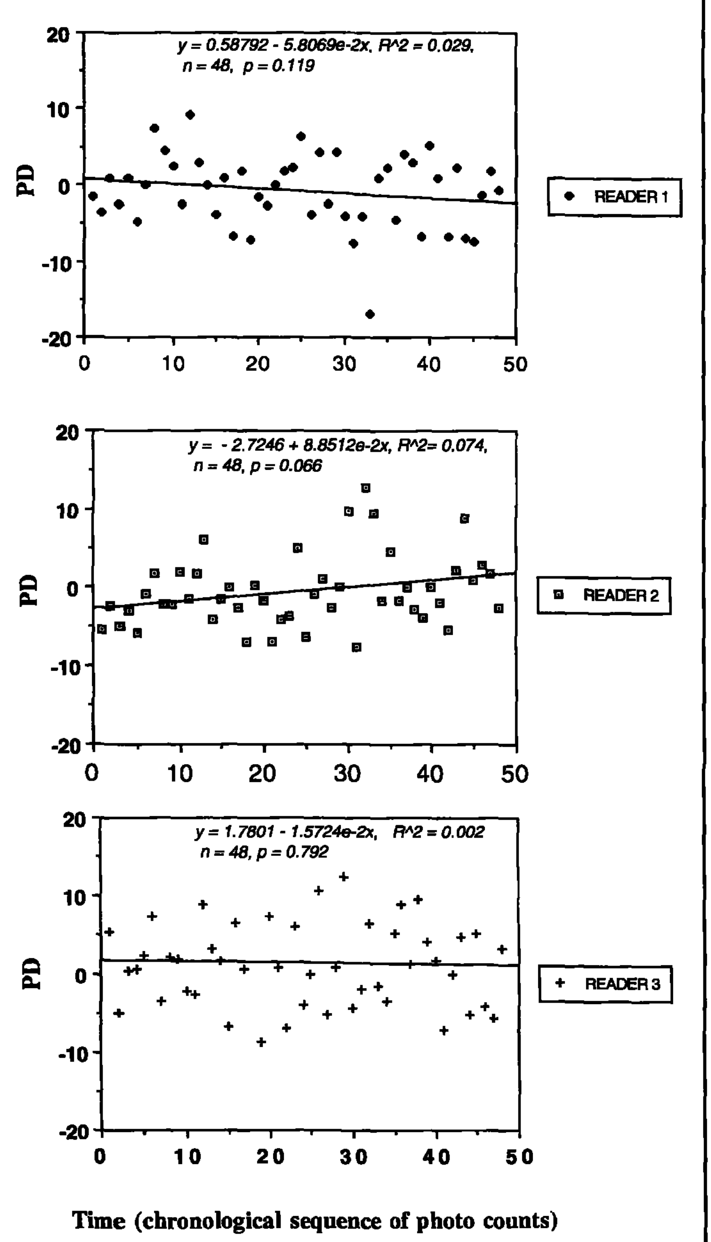

Figure 4

Percent deviation (PD) values regressed on "time." Time represented the chronological sequence, unique for each reader, in which photographed schools were counted during the counting period. Zero on the y axis represents the mean count while negative and positive values represent the percent deviation of the count from the mean.

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