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A comparison of underwater visual distance estimates made by scuba divers and a stereo-video system: implications for underwater visual census of reef fish abundance

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Abstract. Underwater visual census of reef fish by scuba divers is a widely used and useful technique for assessing the composition and abundance of reef fish assemblages, but suffers from several biases and errors. We compare the accuracy of underwater visual estimates of distance made by novice and experienced scientific divers and an underwater stereo-video system. We demonstrate the potential implications that distance errors may have on underwater visual census assessments of reef fish abundance. We also investigate how the accuracy and precision of scuba diver length estimates of fish is affected as distance increases. Distance was underestimated by both experienced (mean relative error = −11.7%, s.d. = 21.4%) and novice scientific divers (mean relative error = −5.0%, s.d. = 17.9%). For experienced scientific divers this error may potentially result in an 82% underestimate or 194% overestimate of the actual area censused, which will affect estimates of fish density. The stereo-video system also underestimated distance but to a much lesser degree (mean relative error = −0.9%, s.d. = 2.6%) and with less variability than the divers. There was no correlation between the relative error of length estimates and the distance of the fish away from the observer.

Extra keywords: accuracy, bias, precision, sampling error.

Introduction

Visual survey techniques are widely used to determine the abundance of both terrestrial (Caughley *et al.* 1976; Caughley 1977; Cormack *et al.* 1979; Ralph and Scott 1981; Francis 1994) and marine organisms (Estes and Gilbert 1978; Marsh and Sinclair 1989). These techniques were first used for assessing the abundance of reef fishes in the 1950s (Brock 1954; Odum and Odum 1955). Since then they have been further developed and widely applied. Underwater visual census (UVC) techniques have become popular, as they are relatively quick, non-destructive, repeatable and cost effective (St. John *et al.* 1990; English *et al.* 1994; Watson *et al.* 1995; Thompson and Mapstone 1997). These techniques also have several disadvantages and biases (see Harvey *et al.* 2002*a*). Three different types of UVC techniques are commonly used: transects; point counts; and rapid visual censuses (RVC) or timed counts. Strip transects are the most common (Kingsford and Battershill 1998). When assessing the abundance of reef fish using a strip transect, a scuba diver normally swims along a marked transect rope or tape measure of a predetermined length and counts all the fish encountered within a set distance on either side of the centre of the transect over a predetermined distance. Point counts are slightly different in that the scuba diver counts all the fish within a circle of a predetermined radius. During RVC counts, the scuba diver records all fish seen within a lane of estimated width during a predetermined time, effectively making many RVC techniques a strip transect of variable length. A feature common to all of these techniques is that the scuba diver has to decide whether a fish is inside or outside the boundary of the sampling unit. In all cases the scuba diver will subconsciously or consciously estimate the cross substratum distance to the fish, and decide whether to include the fish in the count. Some researchers physically mark the boundary of their transects or point counts but many do not, making the task for the scuba diver even more demanding (Bell 1983; Choat and Bellwood 1985; Thresher and Gunn 1986; McCormick and Choat 1987; Lincoln-Smith 1988; Bortone *et al.* 1989; Davis and Anderson 1989; Polunin and Roberts 1993; Rakitin and Kramer 1996; Russ and Alcala 2003). The decision to include or exclude a particular fish is further complicated if the fish moves rapidly across the sample unit boundary (Watson *et al.* 1995). The scuba diver then has to decide whether the fish was inside or outside the sample unit when it was first sighted

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(Andrew and Mapstone 1987). It is clear that systematic errors in distance estimation lead to bias in the count of the number of fish within the sample unit, and hence in the overall estimate of fish abundances (Bohnsack and Bannerot 1986; Thresher and Gunn 1986).

The accuracy and precision of *in situ* UVC length estimates of reef fish has been the focus of some detailed research (Bell *et al.* 1985; St. John *et al.* 1990; Darwall and Dulvy 1996; Harvey *et al.* 2001*a*, 2001*b*, 2002*a*). However, the effect of overestimating or underestimating distance on the accuracy and precision of *in situ* UVC length estimates has not been investigated.

The objectives of this study were to:

(*1*) Compare the accuracy and precision of visual estimates of distance made by novice and experienced scientific scuba divers and a stereo-video system.

(*2*) Demonstrate how errors associated with estimating distance affect abundance estimates of reef fish.

(*3*) Demonstrate the effect of increasing distance on the accuracy and precision of length estimates of fish made by novice and experienced scientific scuba divers under both controlled and field conditions.

Materials and methods

Visual estimates of distance

The accuracy and precision of visual distance estimates made by experienced and novice scientific divers were tested by a simple procedure routinely used to calibrate diver estimates of the lengths of reef fish (GBRMPA 1979; Bell *et al.* 1985; English *et al.* 1994). Typically, PVC sticks or silhouettes of fish are placed in the water and their lengths estimated. The accuracy of the diver estimate is then assessed from the difference between the real size and the estimate. In this study, experienced and novice scientific divers were asked to swim along either a fibreglass surveyor's tape or a lead transect rope marked at 1 m intervals and estimate the distance to each silhouette from marked positions. Sixteen plastic silhouettes of fish, ranging in length from 10 to 49 cm, were placed at distances of between 3.0 and 6.6 m from the marked positions. Trials took place in either a saltwater aquarium or a freshwater pool. The maximum distance from which estimates could be made was 6.6 m because visibility was never greater than 7 m in the saltwater aquaria. Each of the experienced and novice scientific divers swam five repeat transects. The distances from the transect rope and the order of the silhouettes were maintained throughout the experiment. Data were recorded on an underwater slate that was replaced between transects so the divers could not refer back to a previous measurements. Distance data were not made available to the novice or experienced scientific divers between dives to avoid memorisation of previous distance estimates for a particular silhouette. The mean error, standard deviation and the standard error for each of the 16 fish were calculated for the novice and experienced scientific divers.

In many respects the trial represents a best case scenario. The silhouettes were stationary and the scuba divers were given no time limits to estimate the cross substratum distance from the point of observation to the silhouette. Consequently, they had time to use the distance measures on the surveyor's tape or the marked intervals on the lead transect rope to help scale their estimates. Additionally, there were many other objects in the saltwater aquarium (e.g. building bricks, tiles, fish and support pillars) and in the swimming pool (swimmers and lane markings) that could be used to scale the estimates.

Novice scientific divers

Novice scientific divers were defined as experienced scuba divers who had made few, if any estimates of the lengths of reef fish underwater but were all experienced at undertaking scientific observations in other disciplines. Eight novice scientific divers made visual underwater distance estimates in a saltwater pool at the Portobello Marine Laboratory (PML; University of Otago, Dunedin, New Zealand) between May 1994 and January 1995. No more than two transects were completed on any one day except for one diver who completed four consecutive transects in one day.

Experienced scientific divers

Experienced scientific divers were considered active marine scientists who had been, or who were currently involved in research that required them to make counts of reef fish abundance. Five experienced scientific divers made underwater visual estimates of the distances to the plastic silhouettes between October 1994 and June 1996. Three of the divers made their estimates in a saltwater pool at PML while the other two made their estimates in freshwater swimming pools elsewhere. Due to time constraints of diver availability, all of the distance estimates were made on consecutive transects during one dive.

Water clarity is a factor that may change substantially throughout a dive or between dives. During the testing carried out for this research, water clarity between the saltwater and freshwater pools was different, but was consistent during each dive. Therefore, the visual estimates partly replicate the expected conditions in the field and variation in distance estimates analysed for this research are likely to be more accurate and precise than those gathered under field conditions.

Stereo-video estimates of distance

Stereo-video camera estimates of distance were obtained on 20 November 1997 in a freshwater swimming pool. Three silhouettes of different lengths were held in front of the stereo-video camera and their images recorded at 1 m intervals between 3 and 12 m. Three replicate images were recorded for each silhouette at each distance. The mean of ten repeat measurements was calculated for each of the three replicate images recorded for each of the three silhouettes at each distance. The actual distance, from the silhouette to the centre of the camera, was measured using a fibreglass surveyor's tape. A detailed description of the stereo-video system, calibration and measurement procedures may be found in Harvey and Shortis (1996, 1998) and Shortis and Harvey (1998).

Assessing the effect of distance error on estimates of abundance

A hypothetical model was created to demonstrate graphically the potential impact of distance errors and bias on UVC estimates of reef fish abundance. The results presented here are based on point counts only, as the results for strip transects are very similar and any general conclusions are equally applicable (Harvey 1998).

Radial distances for published point counts range from 3 m (Francour 1997) and 5.64 m (Bortone *et al.* 1989) to 15 m (Thresher and Gunn 1986). Francour (1997) notes that the radial distance scanned should correspond to two-thirds of the maximum visibility. Most commonly, radial distances of 7.5 m (Bohnsack *et al.* 1994) and 7 m (Samoilys 1992; Samoilys and Carlos 1992; Jennings and Polunin 1995) have been used.

To keep with common practice, we used a radial distance of 7 m for the theoretical point count in our two-dimensional model. This point count, covering an area of 154.1 m^2 was positioned in the centre of a theoretical 20 m × 20 m square (400 m^2). Circles representing the upper and lower 95% confidence interval (CI) for the range of the actual area censused by novice and scientific divers and the stereo-video system were also created (Fig. 1*a*–*c*). We calculated a 95% CI for the actual

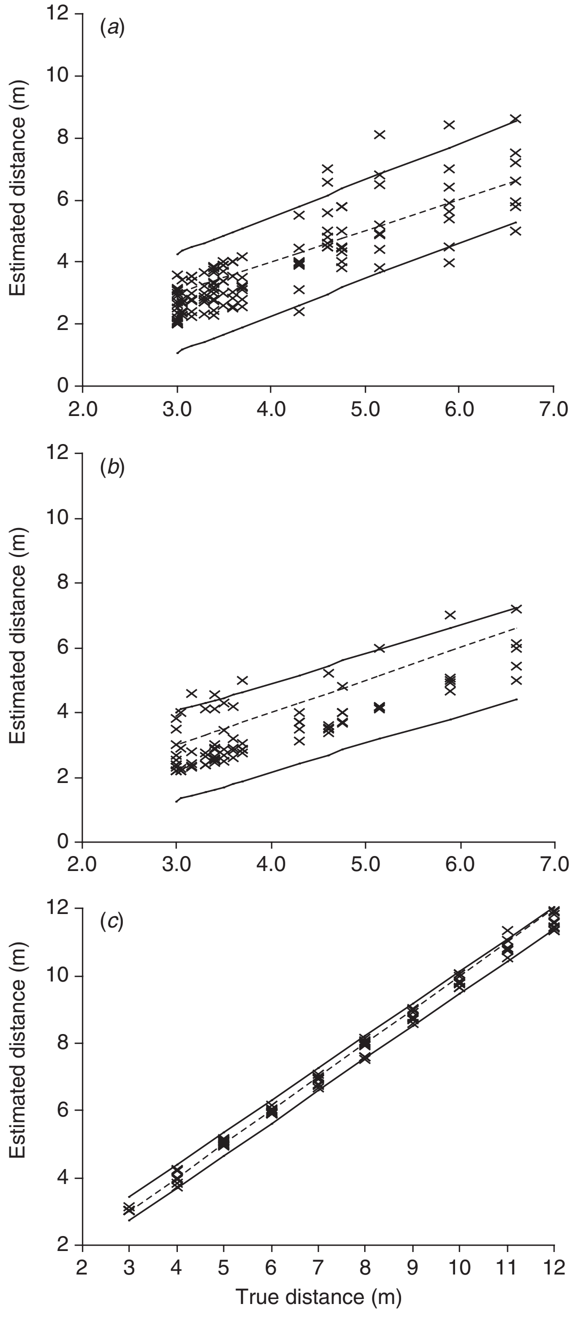


Fig. 1. The accuracy of visual estimates of distance by (*a*) experienced and (*b*) novice scientific divers and (*c*) a stereo-video system. The estimates are represented by the crosses while the dotted line represents the real distance. The solid lines above and below the dotted line represent the 95% CI.

distance associated with an estimated distance, using inverse regression (Draper and Smith 1981). The confidence interval for the actual distance was then converted into a confidence interval for the actual area censused, from which we calculated the potential error associated with the estimated fish density. Potential error in estimated fish density was determined by randomly allocating 50 points, symbolising fish, a location within the 20 m × 20 m square. Counts were then made of the number of fish symbols within the actual area of the point count and the upper and lower 95% CI for the novice and scientific divers and the stereo-video system. This was repeated 50 times based on the confidence intervals for the novice and experienced scientific divers and the stereo-video system.

Assessing the effect of increasing distance on the accuracy and precision of UVC length estimates

Data on the accuracy and precision of *in situ* UVC length estimates by novice and experienced scientific divers were collected in the same experiment and manner as described above with divers estimating the length of each silhouette as it was encountered. An analysis of these data has been presented in Harvey *et al.* (2001*a*) but the relationship between errors in length estimates as distance increases was not investigated. Similarly, the accuracy and precision of *in situ* length estimates made in the field by three experienced observers were presented in Harvey *et al.* (2002*a*) but the relationship between the accuracy and precision of length estimates was not investigated. Details of the experimental design can be found in Harvey *et al.* (2002*a*). This paper reports on an examination of the relationships between errors in length estimates and increasing distance using both these datasets.

Analysis of data

Novice and experienced scientific divers

The results for the novice and experienced scientific divers were summarised before further analysis by calculating the mean distance estimate over all transects, for each silhouette and each observer. The repeat transects were therefore used solely to provide a reliable estimate of the error made by each diver on the distance away of each silhouette. The individual divers provide replication. For each diver, the relative error (RE) at each distance was calculated as a percentage using:

$$\mathrm{RE} = \frac{\text{mean estimated distance} - \text{actual distance}}{\text{actual distance}} \times 100$$

where the mean estimated distance was over all transects. The overall RE at each distance was the mean relative error across all observers. The variation at each distance was summarised by the coefficient of variation (CV) among observers of the mean estimated distance. The CV was calculated as:

$$\mathrm{CV} = \frac{\text{s.d. of mean estimated distance}}{\text{actual distance}} \times 100$$

It might be expected that both the error in estimating distance and the variation between observers would be proportional to the distance. This would imply that RE and CV would both be consistent across a range of distances, allowing us to assume a single overall RE and CV. We checked this by regressing both RE and CV against distance.

Stereo-video distance

For each replicate image, the RE for each combination of distance and silhouette was calculated as for observers, with the mean estimated distance over the ten repeat measurements. The overall RE for each combination of distance and silhouette was the mean across the three images. The variation at each combination of distance and silhouette was summarised by the CV among images of the mean estimated distance. As for the divers, we regressed both RE and CV against distance to check their consistency across a range of distances.

Length data

Errors in length estimates from novice and experienced scientific divers and from the three experienced field observers were converted to relative error (RE; Harvey *et al.* 2001*a*, 2002*a*), graphically summarised and the relationships between error in increasing distance were explored by regressing RE against distance analysis. Regression analysis was used because it might be expected that errors in length estimates would be proportional to the distance. Length errors were converted to RE because fishes of different lengths were estimated over a range of distances. Length errors associated with field estimates were made by comparing the scuba diver estimate to simultaneous measurements with a stereo-video system. The upper or lower 95% CI for the stereo-video lengths were used as an accurate range of values to compare to the scuba diver estimates, and therefore these data represent a best case scenario (Harvey *et al*. 2002*a*). The accuracy and precision of stereo-video estimates of fish length as distance increases are reported in Harvey *et al*. (2002*b*).

Results

Visual estimates of distance

Novice scientific divers

Novice scientific divers tended to underestimate distances (mean error = −6.25 cm, s.e.m. = 25.62 cm; Fig. 2) and had a mean RE of −5% (Table 1). Also, RE increased with distance ($t = 2.97$, d.f. = 14, $P = 0.010$), and ranged from −20% to 16%. Similarly, CV for novice scientific divers increased with distance ($t = 2.37$, d.f. = 14, $P = 0.030$). Coefficient of variation values ranged from 13% to 26% with a mean of 17.9% (Table 1).

Experienced scientific divers

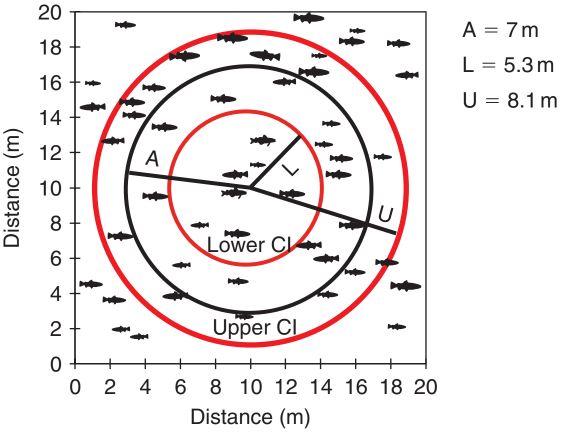
Experienced scientific divers also tended to underestimate distances (mean error = −46.22 cm, s.e.m. = 32.44 cm; Fig. 2) and had a mean RE of −11.7% (Table 1). For experienced scientific divers there was no evidence that RE changed with distance ($t = -0.52$, d.f. = 14, $P = 0.614$). The RE values ranged from −17% to −8%. The CV for experienced scientific divers significantly decreased with distance ($t = -3.14$, d.f. = 14, $P = 0.007$). The CV ranged from 9% to 34% with a mean of 21.4% (Table 1).

Stereo-video

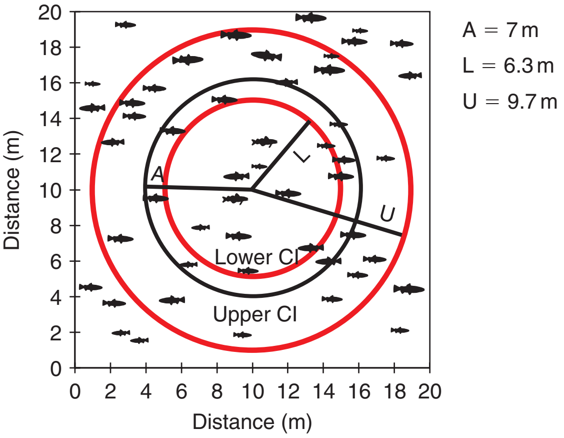
Estimates made from stereo-video also tended to underestimate distance, but to a much lesser degree. A mean error of −10.24 cm (s.e.m. = 5.14 cm) was recorded across all distances and decreased to −0.25 cm (s.e.m. = 3.51 cm) between distances of 3 and 7 m, comparable to the distances over which divers were tested. For stereo-video, RE decreased with distance ($t = -8.19$, d.f. = 28, $P < 0.0001$). The RE values ranged from −3.8% to 2.4%. There was no evidence that CVs for stereo-video changed with distance ($t = -0.58$, d.f. = 28, $P = 0.57$). The CV values ranged from 0.02% to 6.9%.

During underwater recordings it was noted that over larger distances sag in the surveyors tape could not be completely eliminated, even though the tape was pulled taut. The effect of the tape sagging can be seen in the differences in the mean errors for all distances and for those up to 7 m, with an increasing mean negative error and increasing variation at 7 m and beyond (Fig. 2).

(*a*) Novice scientific divers



(*b*) Experienced scientific divers



(*c*) Stereo-video

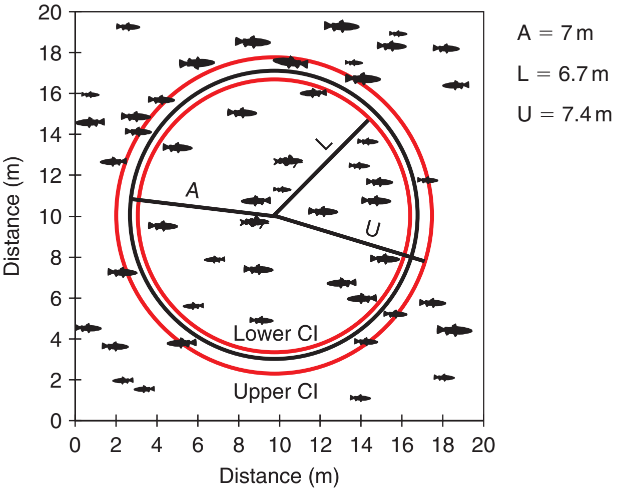


Fig. 2. The effect of error in distance estimates for (*a*) novice; (*b*) experienced scientific divers; and (*c*) a stereo-video system on the actual area censused for a 7 m point count. The actual border of the point count is represented by the middle black line (A) while the outer and inner lines represent the upper (U) and lower (L) confidence intervals of the borders. The symbolised fish help to visualise the potential effect that distance error may have on counts of fish abundance.

Table 1. Summary statistics for visual distance estimates made by novice and experienced scientific divers and an underwater stereo-video system

The coefficient of variation shown is the average over the set of true distances

	Scientific divers		Stereo-video
	Novice	Experienced	
Relative error			
Mean	−5.0%	−11.7%	−0.9%
s.d.	18.6%	18.1%	2.6%
Minimum	−44%	−29%	−7%
Maximum	+58%	+46%	+7%
Coefficient of variation	17.9%	21.4%	2.1%

Table 2. Confidence limits for the true radial distance and area censused during a point count based on visual distance estimates made by novice and experienced scientific divers and an underwater stereo-video system

All limits are expressed as percentages of the estimate, for a point count with a nominal radial distance of 7 m

	Scientific divers		Stereo-video
	Novice	Experienced	
Distance			
Lower	76%	91%	96%
Upper	116%	139%	106%
Area			
Lower	58%	82%	93%
Upper	134%	194%	113%

Effect of distance error on sampling area and counts of abundance: point counts

Novice scientific divers

The actual boundary of a 7 m point count, as perceived by novice scientific divers, could in reality lie between 5.3 m and 8.1 m. An accurate 7 m point count will census an area of 154.1 m^2. According to these results the actual area censused by novice observers may range between 89.0 m^2 and 207.40 m^2 or between 58% and 134% of the actual area (Fig. 1*a*; Table 2). In terms of abundance, as few as 13 fish may be counted if the novice observer overestimates distance or as high as 31 fish if the observer underestimates distance (Table 3).

Experienced scientific divers

A fish estimated by an experienced scientific diver as being at the edge of a 7 m point count could actually be at a distance of between 6.3 m and 9.7 m. The actual area of the census ranged between 127.7 m^2 and 286.8 m^2 or between 82% and 194% of the real area (Fig. 1*b*; Table 2). For the estimated 154.1 m^2 supposedly censused by the point count, abundance could range from as low as 18 fish (lower 95% CI) to as high as 35 fish (upper 95% CI; Table 3).

Table 3. Confidence limits for the actual area censused during a point count and the numbers of fish counted within each interval

All limits are expressed as m^2 or numbers of fish for a point count with a nominal radial distance of 7 m

	Scientific divers		Stereo-video
	Novice	Experienced	
Area			
Lower	89.0 m^2	127.7 m^2	143.7 m^2
Upper	207.4 m^2	286.8 m^2	173.9 m^2
Actual	154.1 m^2	154.1 m^2	154.1 m^2
Abundance			
Lower	13	18	20
Upper	31	35	24
Actual	20	20	20

Stereo-video

Using a stereo-video, a fish estimated as being at the edge of the 7 m point count could actually be at a distance of between 6.7 m and 7.4 m, with the actual area censused being between 143.7 m^2 and 173.9 m^2 (Fig. 1*c*). The actual area censused will fall between 93% and 113% of the actual area (Table 2). In terms of fish counted, abundance estimates may range from 20 fish (lower CI) to 24 fish (upper CI; Table 3).

The relationship between in situ *length estimates and increasing distance*

The relative error of length estimates made in a controlled environment by novice and experienced scientific divers was not significantly correlated to distance (Fig. 3*a*,*b*). Regressing relative error against distance shows weak relationships between relative error and distance (Novice scientific divers: $R^2 = 7.1\%$, RE novice $= -0.23 + 0.07$ distance; Experienced scientific divers: $R^2 = 10.4\%$, RE experienced $= -0.34 + 0.06$ distance).

The magnitude of the relative error of length estimates for experienced scientific divers operating under field conditions indicates there was no significant correlation to increasing distance (Fig. 4*a*,*b*). This was supported by the regression analysis, which shows weak relationships between relative error and increasing distance (Diver 1: $R^2 = 0.9\%$, diver 1 RE = 0.19–0.03 distance; Diver 2: $R^2 = 1.8\%$, diver 2 RE = 0.50–0.08 distance; Diver 3: $R^2 = 7.9\%$, diver 3 RE = 0.43–0.09 distance).

Discussion

Both inexperienced and experienced scientific divers are shown to be unable to accurately estimate the distance to fishes. This influences the total area surveyed in UVC methods. This problem has been recognised previously. Choat and Bellwood (1985) noted that the 5 m distance, which represented half the transect width of their 30 m × 10 m transects, was initially underestimated and that there was a tendency to include larger fish in the transect when they were in fact

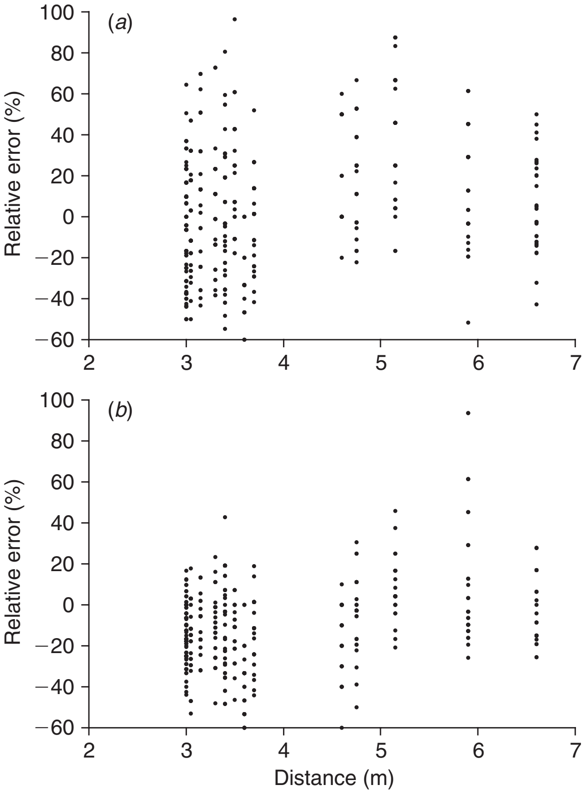


Fig. 3. The distribution of the relative error of length for (*a*) novice and (*b*) experienced scientific divers collected under controlled conditions on silhouettes of fish.

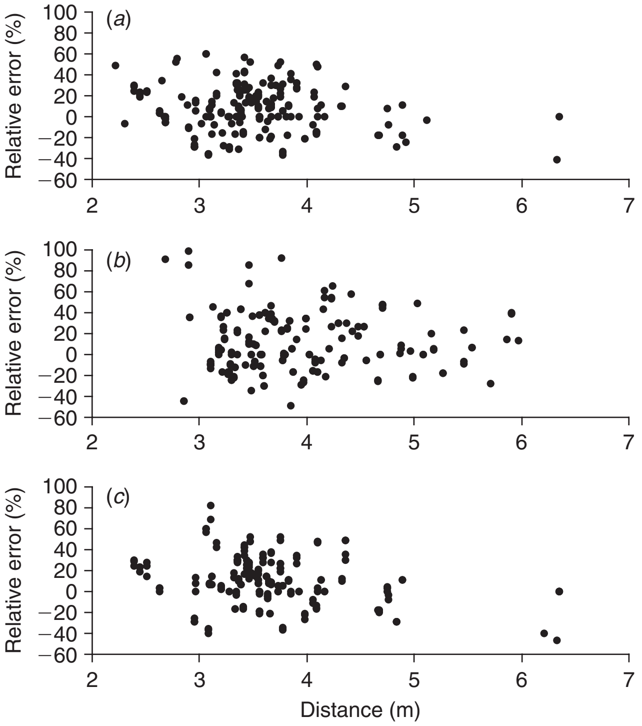


Fig. 4. The distribution of the relative error of length for three experienced scientific divers (a = Diver 1, b = Diver 2, c = Diver 3) collected under field conditions with real fish (n = 200 for each diver).

outside. Four of the five experienced scientific divers used in this research tended to underestimate distances (mean RE = –20%; range = −29–0%), while one tended to overestimate (mean RE = 20%; range = −7–46%). For the novice scientific divers there was a tendency to both overestimate and underestimate (mean RE = −5%; range = −44–58%). Thompson and Mapstone (1997) report that a large proportion of the variation between surveys is attributable to differences between observers. Thresher and Gunn (1986) note that error in distance estimates has considerable influence on the area of the censused sample unit, and consequently the number of fish recorded per sample. Underestimates in distance (i.e. those predominantly recorded by our experienced scientific divers) result in a larger area being surveyed and more fish being counted. Based on the errors recorded by the experienced scientific divers the 95% CI borders indicate that the area censused by an experienced scientific diver could be between 82% and 194% of the actual survey area.

If bias is consistent within and among individual divers then it is possible to compare datasets and develop a calibration equation that allows biased measurements to be corrected (Buckland *et al.* 1993). Therefore, we recommend that distance calibration become a standard practice in UVC in the same way that length calibrations are undertaken (e.g. Bell *et al.* 1985).

Distance estimates made either from the stereo-video system or by the experienced and novice scientific divers were made in controlled environments (saltwater aquaria, swimming pools). It is very likely that the accuracy and precision of distance estimates to a fish made by a diver will decrease when they have to contend with varying conditions of lighting and water visibility in the presence of surges and currents (Harvey *et al.* 2002*a*). Experience has shown that the accuracy and precision of the stereo-video measurements will not change provided calibrations are made within that system and a series of guidelines are followed about how measurements should be made (Harvey and Shortis 1996, 1998; Harvey *et al.* 2001*a*, 2002*b*).

The error and inter-observer variability in estimates of distance as described in this paper have serious implications for comparisons of datasets between different observers and among different surveys sampled at different times. Stereo-video does not completely eliminate error in distance estimates but it does substantially improve the accuracy and precision of estimates. The additional costs of using stereo-video technology include the purchase of two video cameras and underwater housings, a base bar on which to mount the video cameras, a synchronisation diode, a PC frame grabber and the software for analysing the resulting imagery. There is also processing time required back in the laboratory. It has been shown that volunteers can operate both the measurement software in the laboratory and the stereo-video system in the field without compromising data quality (Harvey *et al.* 2001*a*). However, the use of stereo-video raises issues of the detectability of fishes by the cameras. A diver moving along a transect, or within a point count has the advantage of having a greater field of view and can move about the axis of the transect or midpoint of the point count looking into crevices and behind rocks. A stereo-video system points forwards and will not detect fish that are behind rocks or in crevices unless the operator swims the system into those areas. Additionally, a diver can sample at multiple scales whereas the stereo-video system is deliberately preconfigured to sample a specific area.

When sampling multi-species fish assemblages larger and more mobile reef fishes are sampled first using a larger sampling unit (e.g. a 50 m × 10 m transect) and smaller cryptic species are sampled using a more intensive search of a smaller unit (e.g. 50 m × 2 m transects; Kingsford and Battershill 1998; English *et al.* 1994). It is widely accepted that divers carrying out UVC will become overloaded and inefficient when they try to sample too many species at one time (Greene and Alevizon 1989; Kingsford and Battershill 1998; English *et al.* 1994). Perhaps the best combination is for a diver to swim a stereo-video system (Harman *et al.* 2003) while wearing a full-face mask with a microphone to record audio observations onto one of the videotapes in one of the two video cameras (Westera *et al.* 2003).

Surprisingly the data on the relationship between the relative error of UVC length estimates and distance show no relationship as distance increases. This is because the variability in the relative error at all distances is so great that any trends are masked. Errors in length estimates appear to be constant as the distance increases. However, the data do highlight the variability in the precision of the length estimates. This variability will affect the statistical power of programmes using UVC methods to detect changes in the mean length of fish (Harvey *et al.* 2001*b*).

In conclusion, this research demonstrates that error in visual distance estimates made by novice and highly experienced scientific divers can be large, and that this error has the potential to affect the size of the sample units censused. This in turn will affect the numbers of fish counted by a census and the comparison of data collected by different observers and across different censuses by the same observer. It is essential that observer biases inherent in visual surveys are minimised or standardised through calibrations in order to detect changes in fish assemblages using UVC techniques. This is very important for multi-species surveys carried out over large temporal (regional or continental) and/or spatial scales. Particularly in those research programmes investigating the effects of marine protected areas if multi-species datasets collected by different observers at different times are to have any statistical power to support the conclusions they draw. Stereo-video had less error associated with distance estimates than either novice or scientific divers and may offer a cost-effective tool for removing many observer biases.

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