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Michael R. Bower[ab]; Daniel B. Gaines[a]; Kevin P. Wilson[a]; John G. Wullschleger[c]; Maria C. Dzul[d]; Michael C. Quist[de]; Stephen J. Dinsmore[d]
[a] National Park Service, Death Valley National Park, Pahrump, Nevada, USA [b] U.S. Forest Service, Bighorn National Forest, Sheridan, Wyoming, USA [c] National Park Service, Natural Resource Program Center, Fort Collins, Colorado, USA [d] Department of Natural Resource Ecology and Management, Iowa State University, Ames, Iowa, USA [e] U.S. Geological Survey, Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Moscow, Idaho, USA

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ARTICLE

Accuracy and Precision of Visual Estimates and Photogrammetric Measurements of the Length of a Small-bodied Fish

Michael R. Bower,*[1] Daniel B. Gaines, and Kevin P. Wilson
National Park Service, Death Valley National Park, 1321 South Highway 160, Pahrump, Nevada 89048, USA

John G. Wullschleger
National Park Service, Natural Resource Program Center, 1201 Oakridge Drive, Suite 250, Fort Collins, Colorado 80525, USA

Maria C. Dzul, Michael C. Quist,[2] and Stephen J. Dinsmore
Iowa State University, Department of Natural Resource Ecology and Management, 339 Science Hall II, Ames, Iowa 50011, USA

Abstract
We assessed the accuracy and precision of visual estimates from two divers and photogrammetric measurements from a diver-operated stereo-video camera system for determining the length of Saratoga Springs pupfish *Cyprinodon nevadensis nevadensis* (12–36 mm total length) under controlled conditions. Visual estimates by two divers differed significantly from true fish length ($P < 0.001$) but were not significantly different from each other ($P = 0.42$). Levels of accuracy and precision were similar to those previously reported for visual estimates by divers. On average, the two divers underestimated fish length by 2.74 mm (11%) and 2.93 mm (12%). The magnitude of underestimation error increased with fish length. Photogrammetric measurements from a stereo-video camera system were more accurate and precise than diver estimates of fish length. Little to no bias was evident (mean error = 0.05 mm), and the level of precision (coefficient of variation of the difference between observed length and true length) was 4.5% for the photogrammetric measurements compared with 10% and 11% for the two divers' estimates. In comparison with underwater visual surveys, surveys that use a stereo-video camera system may increase the consistency of long-term data sets and improve resolution to detect important length differences in small-bodied fishes. Managers must remain careful to avoid or correct sampling biases, which can affect underwater visual surveys and stereo-video surveys alike.

Given the indeterminate growth of fishes, length is commonly used as a surrogate for age (Anderson and Neumann 1996), particularly when age determination is infeasible or impractical. In addition, age may be less informative for some species than size or life stage (Kirkpatrick 1984). One approach commonly employed to obtain a sample of fish lengths is an underwater visual survey in which observers estimate the length of fish by using self-contained underwater breathing apparatus (SCUBA) or snorkeling equipment. Underwater visual surveys can have advantages over direct capture methods, including the avoidance of handling stress, the ability to survey habitats that are inaccessible to common sampling gears, and potentially

*Corresponding author: mbower@fs.fed.us
[1]Present address: U.S. Forest Service, Bighorn National Forest, 2013 Eastside 2nd Street, Sheridan, Wyoming 82801, USA.
[2]Present address: U.S. Geological Survey, Idaho Cooperative Fish and Wildlife Research Unit, University of Idaho, Post Office Box 441141, Moscow, Idaho 83844, USA.
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greater efficiency (Dolloff et al. 1996). Given these advantages, underwater visual survey techniques have been used in a variety of habitats ranging from coral reefs (e.g., Samoilys and Carlos 2000) to small streams (e.g., Hankin and Reeves 1988).

As in all visual survey methods, sources of sampling and measurement error and bias must be considered for each application (Dolloff et al. 1996). Gear-related size selectivity, where some fish sizes are captured disproportionately, can be problematic in assessment of population size structure (Ricker 1975). Size-specific variation in the probability of fish detection by observers has commonly led to size selectivity in underwater visual surveys (e.g., Sale and Douglas 1981; Fowler 1987; Thurow et al. 2006). Other sources of sampling bias, such as nonrandom fish movements (Watson et al. 1995), fish avoidance of or attraction to divers (Chapman et al. 1974; Stanley and Wilson 1995; Cole et al. 2007; Dearden et al. 2010), and species-specific morphological and behavioral differences affecting detectability (Sale and Douglas 1981; Brock 1982; Sale and Sharp 1983; Fowler 1987), have more commonly been associated with over- or underestimation of population abundance but may also lead to size selectivity in some situations.

While obtaining an unbiased sample of fish lengths is paramount to accurate population assessment (Ricker 1975; DeVries and Frie 1996), optimization of measurement accuracy and precision can also be an important consideration for maximizing statistical power to detect biologically meaningful differences in fish length (Vokoun et al. 2001; Miranda 2007; Quist et al. 2009). In the case of small-bodied fishes such as pupfishes (Cyprinodontidae), for which length differences among early life history stages can be as little as 2 mm (e.g., Gustafson and Deacon 1998), high levels of measurement accuracy and precision may be particularly important. To date, at least five studies have specifically investigated the accuracy and precision of lengths estimated by divers (Bell et al. 1985; St. John et al. 1990; Harvey et al. 2001a, 2002; Edgar et al. 2004). St. John et al. (1990) described average observer errors of 14% of true fish length for a relatively small coral reef fish ($\sim$12.5–47.5 mm). Edgar et al. (2004) reported average observer errors of 7% for several reef-dwelling species varying in size from 175 to 400 mm. Patterns of bias in length estimates can also vary among observers (St. John et al. 1990; Harvey et al. 2001a, 2002), potentially affecting the comparability of results, though training and calibration routines have been used to correct observer biases for some taxa (Bell et al. 1985). In other cases, variation in length estimates among observers has been relatively small (Edgar et al. 2004).

Recently, photogrammetric methods have become a viable alternative to visual surveys for obtaining a sample of fish lengths (reviewed by Shortis et al. 2009). Standard software, calibration routines, and hardware are now available to simplify underwater measurement of fish lengths by using diver-operated or stationary stereo-video camera systems. These systems can have the advantage of being free of common observer length-estimation biases while being more precise than visual length estimates (Harvey et al. 2001a, 2002, 2003, 2010). Consequently, photogrammetric methods often result in greater statistical power to detect differences in fish length (Harvey et al. 2001b, 2002). Using a stereo-video camera system in an aquarium, Harvey et al. (2003) reported a mean measurement error of -0.4 mm (SE $= 0.3$ mm) from photogrammetric measurements of a variety of species varying in length from 180 to 590 mm. Similarly, Harvey et al. (2003) found a mean measurement error of 1.72 mm (SE $=$ 1.1 mm) for large (830–1,412 mm) southern bluefin tuna *Thunnus maccoyi* in sea cages. Although these results are encouraging, the accuracy and precision of such a stereo-video camera system for measuring the length of small-bodied (i.e., $<$40 mm) fishes have not been studied.

We evaluated both underwater visual surveys and stereo-video camera system surveys for potential use in long-term monitoring of population size structure for small-bodied fishes. Our specific objective was to determine the accuracy and precision of (1) visual estimates by divers and (2) photogrammetric measurements from a diver-operated stereo-video camera system of length of the small-bodied Saratoga Springs pupfish *Cyprinodon nevadensis nevadensis*.

METHODS

Stereo-video camera system.—A SeaGIS underwater stereo-video camera system (SeaGIS Pty. Ltd., Bacchus Marsh, Victoria, Australia) consisting of a pair of Canon Vixia HV30 high-definition cameras (Canon USA, Inc., Lake Success, New York) mounted within polyvinyl chloride and acrylic housings and affixed as a stereo-pair to an aluminum base bar was used. The system was similar to the prototype described by Shortis and Harvey (1998) that was developed for measuring pelagic marine fishes. However, our system was optimized for measurement of small-bodied fishes at distances of approximately 1.5 m by scaling down system components and eliminating wide-angle lens adaptors. The cameras were configured with a base separation of 430 mm and an inward convergence angle of approximately 7° per camera. A flashing light-emitting-diode array was centered in front of the two cameras and was used to synchronize images in time. Video imagery was recorded by the two cameras onto Sony DVM60PRR MiniDV digital video cassettes, which were subsequently captured to Audio Video Interleave digital format with Neo Scene version 1.6.0 (Cineform 2009) for use in photogrammetric calibration and measurement software.

System calibration.—An in situ calibration routine was performed for the stereo-video camera system on the morning of the experiment by following the methods of Shortis and Harvey (1998). A calibration cube ($0.5 \times 0.5 \times 0.3$ m) containing approximately 85 targets was filmed with the stereo-video camera system in 20 different orientations. Using the program CAL (SeaGIS 2009a), images were synchronized, key reference targets were located in both images, and physical camera parameters as well as camera separation and orientation parameters were computed to allow photogrammetric measurement.

Experimental procedure.—Saratoga Springs pupfish were collected from Lake Tuendae at the Desert Studies Center located in Mojave National Preserve, California, for use in the experiment. The experiment was conducted in a swimming pool (3 m wide × 4 m long × 1 m deep). For the duration of the experiment, the pool was maintained as a flow-through system to sustain suitable water quality and limit turbidity. The pool was partially lined with a camouflaged fabric to mimic the background against which fish length is typically estimated in natural fish habitats. The pool was shaded to avoid overexposure of video imagery and to mimic the low-light conditions of most fish habitats. One at a time, fish were introduced into the pool, where they were filmed with the stereo-video camera system while two divers concurrently estimated their lengths. As is typical under field conditions, divers were allowed to approach the fish and compare it with a measurement slate if needed to calibrate their estimates. Given that both divers estimating lengths in this study had extensive experience estimating the lengths of Devils Hole pupfish *C. diabolis*, they received no additional training in length estimation. Stereo-video imagery of the fish was filmed at a distance of roughly 1.5 m, although this distance varied among fish as they swam freely in the pool. Divers confidentially relayed their estimates to a data recorder to maintain estimate independence. Fish were then netted and anesthetized in a 0.05-mL/L solution of clove oil for approximately 1 min or until loss of balance. While fish were anesthetized, total length (TL) was measured to the nearest 1 mm on a measuring board and maximum body depth was measured to the nearest 0.01 mm with a digital caliper. Fish were then returned to a second flow-through holding tank for recovery.

Photogrammetric measurements.—Digitized video from the experimental procedure was used to generate length estimates for each fish with the program PhotoMeasure (SeaGIS 2009b). In accordance with the methods of Harvey et al. (2003), five measurements of each fish were made from five different video frames to minimize the effect of fish swimming motion on length measurements.

Data analysis.—The accuracy of the two divers' estimates and the photogrammetric measurements were assessed in comparison with direct board measurements by using the Wilcoxon rank-sum test for paired samples ($\alpha = 0.05$) given violation of the normality assumptions required for parametric tests (Zar 1999). The magnitude and direction of bias for the two divers' estimates and the photogrammetric measurements were summarized by computing the mean difference (i.e., mean error) between observed fish lengths and true fish lengths; true fish lengths were considered equal to the direct board measurements. Precision of length estimates or measurements were summarized by the range, SD, SE, and coefficient of variation (CV = 100 × SD/mean) of differences between observed and true fish lengths. The mean relative error (Harvey et al. 2001a), defined as the average of the differences between observed and true lengths divided by the true lengths, was computed to further describe levels of precision in proportion to fish size and to facilitate comparisons with previous research. The effect of fish length on visual estimates made by divers was assessed with simple linear regression.

TABLE 1. Summary of error (i.e., difference between observed length and true length) in diver estimates and photogrammetric measurements of total length for Saratoga Springs pupfish. Relative error (%) is 100 times the average of differences between observed length and true length divided by true length. The coefficient of variation (CV, %) is 100 times the SD of error divided by mean fish length.

Statistic	Diver 1	Diver 2	Stereo-video
N	117	117	109
Mean error (mm)	−2.74	−2.93	0.05
SD (mm)	2.23	2.49	1.03
SE (mm)	0.21	0.23	0.10
Range (mm; minimum, maximum)	12 (−7, 5)	13 (−11, 2)	5 (−2, 3)
Relative error (%)	−10.91	−11.90	0.59
CV (%)	9.60	10.73	4.50

RESULTS

Visual Estimates

Visual TL estimates for 117 fish were made by the two divers. Fish varied in length from 12 to 36 mm TL (mean ± SE = 23 ± 0.7 mm). Visual estimates by both divers differed significantly from true length (diver 1: Wilcoxon rank-sum test statistic [W] = 155, $P < 0.001$; diver 2: $W = 148$, $P < 0.001$) but were not significantly different from each other ($W = 1{,}932$, $P = 0.42$). Diver 1 and diver 2 underestimated TL by an average of 11% and 12%, respectively, and had similar levels of precision (Table 1). The magnitude of error increased with fish length (Figure 1), and the relationship between length estimate error and true fish length was significant for diver 1 ($r^2 = 0.48$, $N = 117$, $P < 0.001$) and for diver 2 ($r^2 = 0.40$, $N = 117$, $P < 0.001$).

Photogrammetric Measurements

Of the 117 fish for which length was visually estimated by the divers, 109 fish were also recorded by video, which generated five photogrammetric TL measurements for each fish. This group of fish also varied in length from 12 to 36 mm TL (23 ± 0.7 mm). Measurements of body depth were not feasible because the fish were oriented slightly below the cameras, resulting in video images that did not expose the entire vertical profile of the fish for measurement. The average of five TL measurements made for each fish by means of the stereo-video camera system was not significantly different from true fish length ($W = 2{,}832$, $P = 0.74$). Little to no length bias in average photogrammetric measurements was apparent (Table 1; Figure 1). Average photogrammetric measurements for

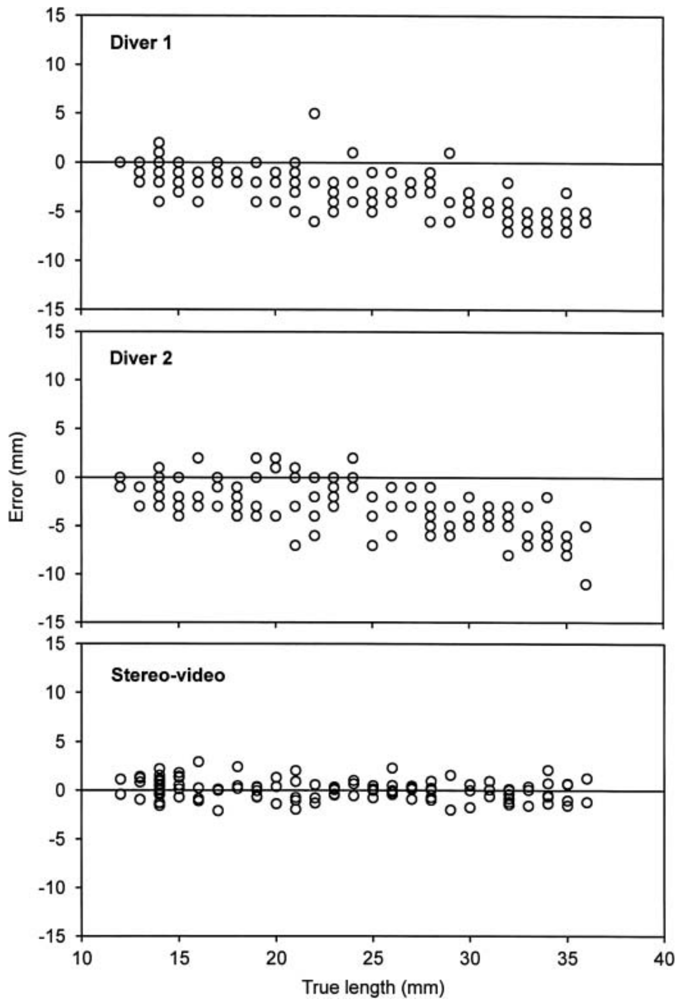

FIGURE 1. Distribution of error (i.e., observed length minus true length) associated with individual Saratoga Springs pupfish total lengths estimated visually by two divers and photogrammetric length measurements obtained with a stereo-video camera system.

individual fish were more accurate and more precise than the divers' visual estimates (Table 1).

DISCUSSION

One common pattern of error in visual length estimates is that divers tend to overestimate the size of smaller fish and underestimate the size of larger fish in a sample (e.g., Harvey et al. 2002; Edgar et al. 2004), although individual divers can have unique biases (e.g., St. John et al. 1990; Harvey et al. 2001b, 2002). In our study, both divers tended to underestimate length for fish of all sizes, and the magnitude of error increased with fish length. The divers' tendency to underestimate the lengths of fish from all size-classes could be a consequence of diver experience or training. Bell et al. (1985) and St. John et al. (1990) found diver experience to affect the accuracy and precision of length estimates. Both divers completing length estimates in the present experiment had been conducting visual surveys of Devils Hole pupfish length for more than 10 years. Devils Hole pupfish are somewhat shorter than Saratoga Springs pupfish (i.e., maximum length is roughly 10 mm less), potentially helping to explain the divers' tendency to underestimate fish length across the range of lengths encountered in this study.

The accuracy and precision of divers' length estimates in our study were within the range previously reported. In some cases, these levels of accuracy and precision could be insufficient for detecting important differences in fish length, particularly for short-lived and small-bodied fishes. As one example, the Devils Hole pupfish is a short-lived (i.e., ~1 year), small-bodied (i.e., <40 mm TL) endangered species for which there is great conservation concern (Deacon and Williams 1991). Gaining a better understanding of life history characteristics and maintaining a current understanding of population demographics is a priority to improve management efficacy. Gustafson and Deacon (1998) identified four early life history stages that were thought to correspond to important developmental stages for the Devils Hole pupfish. Within each stage, fish vary in length by 2–4 mm. As such, the tendency of both divers to underestimate fish length by approximately 3 mm would strongly bias estimates of abundance for these early life history stages. Average diver biases would need to be regularly assessed and corrected by using either training routines (e.g., Bell et al. 1985) or post hoc adjustments (e.g., Edgar et al. 2004) to achieve visual estimates that are of sufficient accuracy for monitoring changes in the abundance of Devils Hole pupfish early life history stages. However, the precision of the two divers' estimates (i.e., CV = 10% and 11%) may still obscure important changes in the abundance of individual life stages. For other information needs, a lesser degree of accuracy and precision may suffice. For example, monitoring changes to mean length in a population as an indication of broad shifts in length structure probably could be accomplished by using divers' visual estimates with little or no correction for bias.

The stereo-video camera system used in our experiment enabled highly accurate and precise photogrammetric measurements of a small fish in a controlled setting. The length of fish in our study was more than an order of magnitude smaller than the length of fish studied by Harvey et al. (2003), but we achieved similar levels of accuracy and precision in proportion to fish length. The mean relative error was 0.59% in our study compared with 0.16% reported by Harvey et al. (2003). Similar to Harvey et al. (2001a, 2003), we found the act of resolving the fish's endpoint from the environmental background to be a major source of photogrammetric measurement error. In our experiment, operators of photogrammetric measurement software were novices. Harvey et al. (2001a) suggested that measurement error can be reduced by increasing the experience of photogrammetric software operators. Furthermore, while the full high-definition cameras used in our study provide sufficient image resolution for accurate and precise photogrammetric measurement (Harvey et al. 2010), future enhancements in image resolution may reduce the subjectivity of fish endpoint identification. Consideration should also be given to alternative measures of fish length (e.g., standard length), which may improve the consistency of fish endpoint resolution, particularly for small fishes with translucent caudal fins.

In the current experiment, we found the video quality to be sufficient to make five repeated measurements of most fish. However, in an early trial rapid algal growth over the course of the day resulted in declining water clarity. Whereas Harvey et al. (2001a) found their measurements from a stereo-video system to be robust to changes in water clarity, the greatly reduced video quality experienced during our early trial made photogrammetric measurement infeasible.

Obtaining an unbiased sample of fish lengths from a population is an important sampling design consideration that we did not investigate but is critical to the use of length data obtained by either underwater visual surveys or by stereo-video camera system surveys. Our experiment was conducted under controlled conditions, and though we attempted to design our experiment to resemble natural habitats (e.g., we used a camouflaged background), we controlled for sources of sampling bias by selecting individual fish for measurement one at a time. This was necessary to isolate sources of measurement error. In visual surveys conducted in natural habitats, size-dependent variation in fish detection probabilities can bias samples toward larger or more active fish (e.g., Sale and Douglas 1981; Fowler 1987; Thurow et al. 2006). As this pattern of sampling bias can occur in a variety of habitats and with a variety of species, it seems logical that it would affect samples of pupfish lengths from natural habitats; however, the magnitude of this effect is likely to vary among observers and fish populations. Managers should consider conducting pilot studies to evaluate alternative sampling designs that could minimize size selectivity and other sources of sampling bias before finalizing long-term population monitoring methods.

Managers considering underwater visual surveys or diver-supported stereo-video camera system surveys should also consider the logistical constraints of time and money. In general, the logistical demands of diver-supported surveys (i.e., snorkel or SCUBA) can be substantial for both methods. The operation of a stereo-video camera system can increase dive complexity, particularly in SCUBA-supported surveys, where the preexisting task load for divers is substantial. Surveys that employ stereo-video camera systems also require additional time and expense to acquire and maintain equipment, train staff in system and software operation, and complete system calibrations. Perhaps most importantly, although semiautomated processes that streamline fish recognition, counting, and measurement from stereo-video imagery are being developed (Shortis et al. 2009), the manual processing of imagery to obtain fish lengths currently represents a substantial time commitment. However, this time commitment may be partially offset by the reduced need to complete replicate surveys to achieve the desired level of statistical power.

In summary, the stereo-video camera system provided increased accuracy and precision for measuring the lengths of small-bodied fish in relation to the estimates produced by two divers. For some information needs, the precision of diver estimates of fish length may provide sufficient resolution, particularly if accuracy is improved by a combination of observer training and estimate calibration. However, the increased precision of measurements generated by using a stereo-video camera system could improve the ability to detect biologically important differences in fish length, particularly for short-lived and small-bodied fishes, or could reduce the need to replicate surveys to achieve a desired level of statistical power. The stereo-video camera system resembled an impersonal measurement system that was largely free of bias and could allow for improvements in the consistency of long-term data sets used for population monitoring. To achieve accurate population assessment, managers must remain careful to avoid or correct sampling-related biases in underwater visual surveys and stereo-video camera system surveys alike.

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