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Using relative eye size to estimate the length of fish from a single camera image

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ABSTRACT: Estimating fish sizes from camera images is an important requirement of many fish monitoring programs, typically involving complex and expensive technology such as stereo-video. However, as a fish grows, the relative size of its eye typically decreases, providing a potential means of estimating fish size from a single image. We show that the ratio of head height to eye diameter is a good predictor of body length for 6 species of common New Zealand reef fish representing 6 different families. The regression equations describing such relationships can be used to estimate lengths of individual fish from single photographs or video frames, which in turn can be used to estimate the distance of each fish from the camera (by determining the proportion of the image frame occupied by an object of known length at known distances) in order to standardize the survey area. In a field test, lengths of 90% of 511 individual snapper *Pagrus auratus* recorded by unbaited video cameras could be estimated from their head height:eye diameter ratios. This method enables fish lengths to be estimated from single still or video images, allowing fish to be monitored with small inexpensive cameras. While this simple and cost-effective approach will increase the accessibility of video monitoring techniques, it will be best suited to areas where fish diversity is low enough to enable equations to be obtained for all common species, or where the focus is on a subset of species (e.g. harvested species).

KEY WORDS: Fish · Length estimation · Monitoring · Photogrammetry · Survey

INTRODUCTION

Body size affects nearly all aspects of an organism's biology and ecology (Peters 1983, Schmidt-Nielsen 1984) and is central to the management of exploited species. A variety of methods is used to survey sizes of reef fishes underwater. Divers can estimate fish lengths to acceptable levels of accuracy and precision for most purposes following training, but researcher time underwater is limited and survey data may be biased by positive or negative responses of fish to divers (Cole 1994, Kulbicki 1998, Watson & Harvey 2007, Dearden et al. 2010, Dickens et al. 2011). Remote still or video cameras can operate at greater depths and for longer bottom times than divers, and may have a smaller effect on fish behavior (Mallet & Pelletier 2014). Lengths of fish captured by camera have been estimated from stereo images taken by 2 cameras (Harvey & Shortis 1995, Harvey et al. 2001, 2002a) and from a scale such as light spots from parallel lasers (Harvey et al. 2002b) or an object of known size like a bait canister (Willis & Babcock 2000). However, these methods have disadvantages. Stereo photography requires 2 synchronized and precisely aligned cameras, so the equipment used is more expensive, sophisticated, delicate and bulky than a single camera system (although cheap action cameras are reducing the cost difference; Letessier et al. 2015), and subsequent image processing is laborious.

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Parallel lasers are useful for estimating lengths of benthic fish on the same plane as the lasers, but fish in the water column are less likely to simultaneously have 2 laser spots on them. Length estimates can be obtained from baited underwater videos using a bait canister or other scale but are prone to error when fish are outside the plane of the scale (Harvey et al. 2002b).

If the relative proportions of body parts were strongly correlated with body length, then the latter could be estimated from a single image. Zeidberg (2004) used this approach to estimate lengths of squid from single video frames, based on the ratio of eye diameter to mantle length (which decreased as individuals grew), and he suggested the method could be applied to fish. The relative size of the vertebrate eye also tends to decrease as individuals grow (Walls 1942, Kiltie 2000). Once a fish's length is estimated from an image, it will be possible to determine how far the individual is from the camera by determining the proportion of the field of view it occupies. Counting only those fish within a certain distance from the camera enables the operator to standardize the area surveyed for fish in the face of spatial and temporal variation in water clarity and light levels.

We examined whether relative eye size can be used to estimate body lengths of fish from single images by determining the relationship between head height:eye diameter ratio and body length for 6 species of common New Zealand reef fish. To estimate how far individuals are from the camera, we determined the proportion of the field of view occupied by an object of known size at different distances. To assess the practicality of this approach, we estimated the size of snapper *Pagrus auratus*, northern New Zealand's most sought-after marine fish (Parsons et al. 2009), from an unbaited video survey in and around the Cape Rodney to Okakari Point Marine Reserve in northern New Zealand.

MATERIALS AND METHODS

Morphological measurements were made of 6 common reef fish species in northeastern New Zealand, with each species representing a different family (Table 1). Dead fish were obtained from the commercial fishery (large snapper) or other researchers (butterfish, small spotties and small snapper). Live fish were captured by divers using a barrier net or hand net. These fish were photographed underwater against a plastic sheet marked with an 80 × 80 mm grid for a scale, then released. For each species we obtained individuals ranging in size from small juveniles to adults at 69 to 97% of their typical maximum length (Table 1).

The following measurements were made of each individual, either directly from dead specimens using calipers and a tape measure, or from digital photographs of live specimens using the software ImageJ: fork length (or total length for those species without forked tails: spotty and leatherjacket), head height (perpendicular to the long axis of the fish, through the centre of the eye), and eye diameter (on the line of the head height measurement) (Fig. 1). Relative eye size was expressed as the ratio of head height:eye diameter rather than vice versa, so that the relationship between relative eye size and body length was positive.

Regressions of length on relative eye size were run using SigmaPlot v.12.5. We plotted 95% confidence intervals and 95% prediction intervals, which show how precisely a specified relative eye size can predict the average length of multiple fish and the length of an individual fish, respectively (following equations 16.28 and 16.29 in Zar 1996). The mean error, the average of the absolute values of the residuals from the regressions, was calculated for each species to facilitate comparisons of precision with existing methods (e.g. Harvey et al. 2002b).

In order to calculate the distance of recorded individuals from the camera, it was necessary to calibrate

Table 1. New Zealand reef fish species sampled for relative eye size–body length relationships. n is the total number of individuals measured, and the number in parentheses is the number that were measured alive underwater

Species	Family	Maximum length (mm) (from Francis 2012)	Lengths of measured individuals (mm)	n
Snapper *Pagrus auratus*	Sparidae	1050	14–725	52 (0)
Leatherjacket *Meuschenia scaber*	Monacanthidae	430	23–311	16 (12)
Goatfish *Upeneichthys porosus*	Mullidae	400	50–296	8 (8)
Red moki *Cheilodactylus spectabilis*	Cheilodactylidae	600	66–496	10 (10)
Spotty *Notolabrus celidotus*	Labridae	310	19–301	15 (11)
Butterfish *Odax pullus*	Odacidae	550	29–475	23 (3)

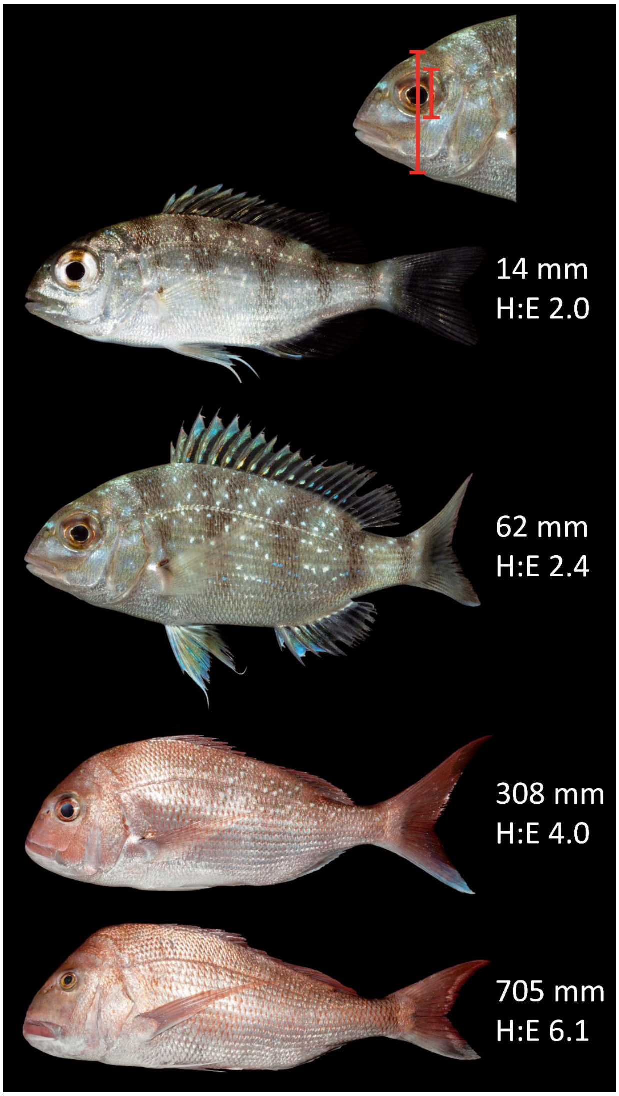

Fig. 1. Individual snapper *Pagrus auratus* of increasing fork length (top to bottom) showing how relative eye size decreases with growth in length. H:E = head height:eye diameter ratio. Red lines on the photo in the top right indicate where measurements were made

our particular camera system (GoPro Hero3+ Silver in a dive housing with flat lens port, set on medium angle view and 1280 × 720 resolution). This was done underwater by holding a horizontally oriented 470 mm long plastic fish in front of the camera at 0.5 m intervals from the housing out to 5 m. The number of pixels spanned by the fish at each distance was later measured using ImageJ, enabling us to derive a relationship between fish length and distance from the camera that could later be applied to any fish whose length had been estimated from its head height:eye diameter ratio. In theory it should have been necessary to correct for the orientation of the fish if it was not horizontal and perpendicular to the camera, but in practice most fish presented perpendicular to the camera at least once as they swam past, and if they did not, it was usually impossible to define their eye well enough to obtain a head height:eye diameter ratio in any case.

To determine the proportion of individual fish whose lengths could be estimated from typical video footage, we used footage from a survey of snapper conducted around the Leigh coastline in northeastern New Zealand. Thirty-six camera drops were done from March to May 2014 between 9:00 and 16:00 h, using the GoPro video camera described above, in a small dark grey plastic housing designed to blend into the rocky seafloor. Three drops were conducted on randomly chosen 5 to 15 m deep reef within each of 6 areas distributed across the Cape Rodney to Okakari Point Marine Reserve and 6 on the adjacent fished coastline. Cameras were deployed by divers and left to record continuously for 2 h. Cameras were only deployed when visibility was at least 5 m, and all snapper that swam by at a distance estimated at greater than 5 m were excluded. All snapper were quantified within alternating 5 min blocks, after excluding the first 5 min, in case fish were affected by the diver deploying the camera (i.e. 1 h total footage was analyzed per deployment). The footage was rewound or fast-forwarded as necessary to find the frame with the best view of each individual snapper (ideally fish were close, perpendicular to the camera lens and with the eye clearly visible). Snapper were categorized as measurable or non-measurable depending on whether the head was clearly profiled with a well-defined eye in at least one frame.

RESULTS

Head height remained a relatively constant proportion of body length as fish grew for 4 of the 6 species (snapper, leatherjacket, goatfish, red moki; Figs. 2A–D) but increased steadily for spotty and butterfish (Figs. 2E,F). Eye size as a proportion of body length decreased steadily for all 6 species (Figs. 2G–L). The ratio of head height:eye diameter exhibited a strong linear relationship with body length for the same 4 species, with $r^2 \geq 0.89$ (Figs. 3A–D). Relationships for the other 2 species, spotty and butterfish, were also strong, but they were better fitted by curves (exponential rise to a maximum), with $r^2 = 0.94$ for both (Figs. 3E,F). The mean error ranged from 18–38mm (Fig. 3), which equated to 9–17% of average body length.

The proportion of the camera field of view occupied by a fish model of known length was a very good predictor of distance from the camera (straight line relationship between 1/number of horizontal pixels and distance, $r^2 = 0.9996$).

A total of 608 snapper were recorded during our survey. We attempted to measure the head height:eye diameter ratios of 511 individuals and were able to do this for 460 (90%). The other 97 fish (mostly juveniles, <270 mm fork length) were in schools, and their lengths were estimated from that of a neighbour considered to occupy the same vertical plane.

DISCUSSION

To our knowledge, this is the first study to show that relative eye size can be used to estimate fish lengths from single photographs or video frames, as suggested by Zeidberg (2004). There were strong relationships between relative eye size and length for all 6 species investigated in this study. This was particularly true for snapper *Pagrus auratus* (Figs. 1 & 3A), which is heavily fished in northern New Zealand and has been the subject of numerous underwater surveys that show size-specific responses to protection within marine reserves (e.g. Willis et al. 2003). Snapper behavior is strongly influenced by divers, requiring the use of remote cameras for underwater surveys (Willis et al. 2000).

Interspecific variation in relative eye size is greater in fish than in other vertebrates (Howland et al. 2004). When regression lines for all 6 species were

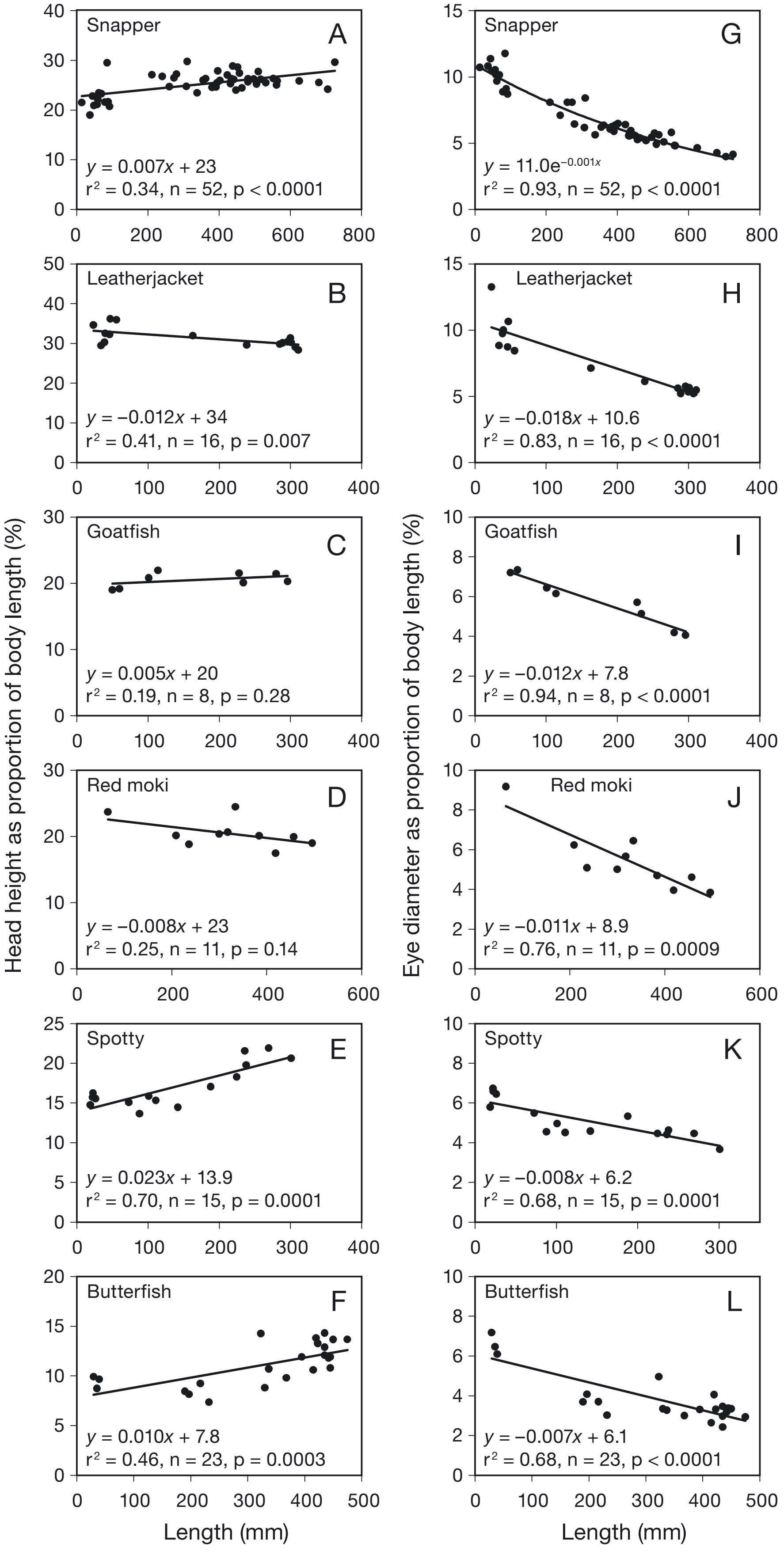

Fig. 2. Body length versus (A–F) head height and (G–L) eye diameter as proportions of body length for 6 common species of reef fish in northeastern New Zealand. Body length is fork length for all species except leatherjacket and spotty (total length). Solid lines represent ordinary least squares regression lines

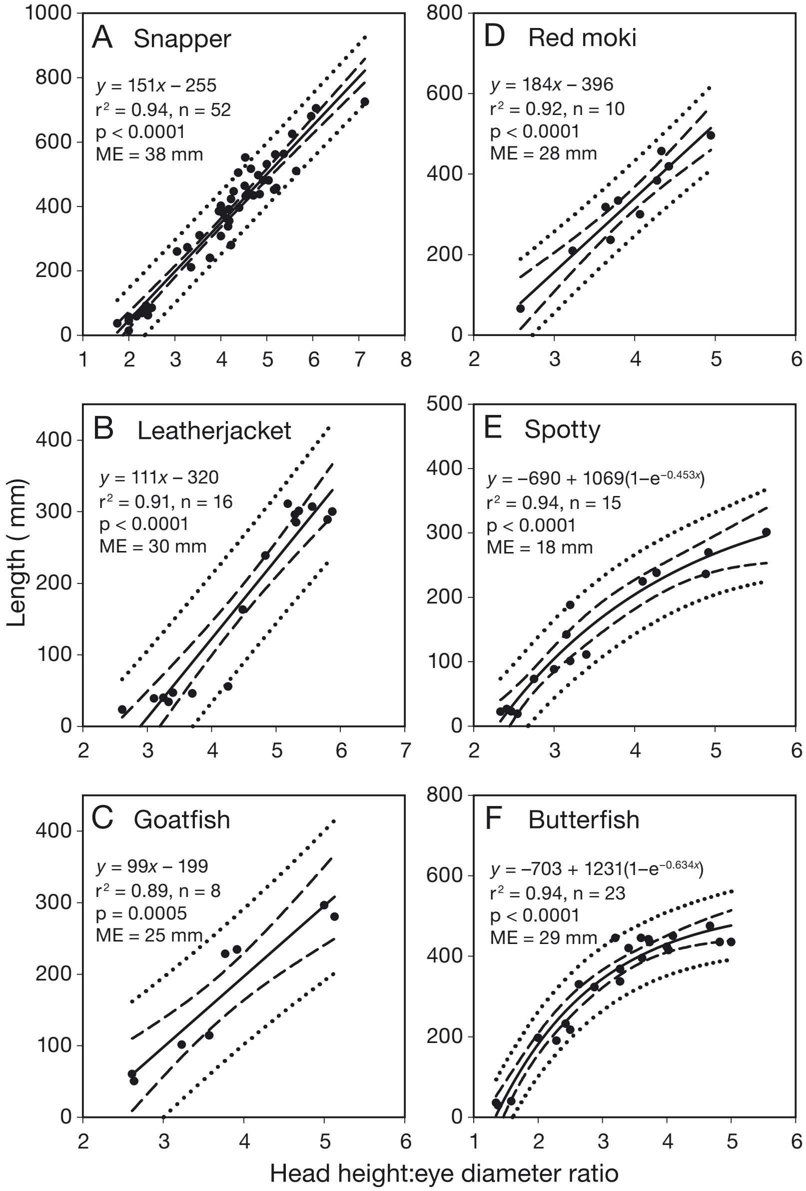

Fig. 3. Relationships between head height:eye diameter ratio and body length for 6 common species of reef fish in northeastern New Zealand. Body length is fork length for all species except leatherjacket and spotty (total length). Solid lines represent ordinary least squares regression lines, dashed lines represent 95 % confidence limits on the regression lines, and dotted lines represent 95 % prediction intervals (describing the precision with which the length of an individual fish with a specified relative eye size is predicted by the regression equation). ME is the mean error (see 'Material and methods' for details)

plotted on the same graph, the relationships between relative eye size and total length were too variable to enable the formulation of a sufficiently precise 'general' equation that could be applied to other species (data not shown), and the variation among species could not be related to an easily obtainable variable such as maximum length, feeding mode, or timing of daily activity (Pankhurst 1989, Schmitz & Wainwright 2011). Our method of length estimation is therefore best suited to studies of species-poor communities or where the focus is on a small number of key species within more diverse communities. It is particularly applicable to exploited fish species, as specimens for measurements of eye diameter, head height and body length should be readily obtainable through local fisheries.

The estimation of fish lengths using relative eye size is subject to many of the same environmental variables that affect other camera-based survey methods, e.g. distance of fish from the camera, water clarity, light level, fish size and camera resolution. Additional variation is introduced due to error in the relative eye size–length relationship, although this error is surprisingly small for the species we examined (Fig. 3). Estimates made using this method are much less precise than those made using stereo-video, with mean errors ranging from 18 to 38 mm for the relationships in Fig. 3 compared with 1 mm for digital stereo-video used to measure fish models at 2 to 9 m distance in a pool (Harvey et al. 2002b). Our errors do not incorporate error associated with measuring eye diameters and head heights of fishes from field video images. However, for many purposes the precision of our method will be adequate. For instance, studies on the effects of marine reserves often bin fishes into a low number of size classes for analyses (e.g. <270 and ≥270 mm fork length; Willis et al. 2003). In the present study, only 7 % of fish recorded by the camera could not be measured, either directly or from an adjacent fish.

The very strong linear relationship between object distance from the camera and the proportion of the frame occupied by an object of known length allows the distance of fish from the camera to be estimated once their body length has been estimated from their relative eye size. This enables the number of fish to be quantified within a standard distance of the camera, so that counts are unaffected by variation in water clarity beyond this distance. The accuracy of the distance estimation therefore depends on the accuracy of the length estimation. Obviously a separate calibration will need to be done for each camera–lens combination used, but this calibration is quick and only needs to be done once.

The correlations between head height:eye diameter ratio and body length were, generally, driven more by ontogenetic changes in eye diameter than by changes in head height. However, in the 2 labroid fishes (spotty and butterfish), relative head height increased slightly with growth (i.e. larger individuals were deeper-bodied), leading to curvilinear relationships between head height:eye diameter ratio and body length.

Eye diameter as a proportion of body length could be used to estimate body length directly, as Zeidberg (2004) showed for squid and suggested for fish, but for 5 of the 6 fish species we examined the head height:eye diameter ratio was correlated more strongly with body length than was eye diameter alone. Additionally, a vertical dimension like head height is less affected than body length by flexion during swimming or the angle of the fish relative to the camera, so will often be easier to measure off images (Karpov et al. 2009).

Our results are consistent with a number of studies reporting negative allometry in the eye sizes of fishes both within and among species (e.g. Howland et al. 2004, McDowall & Pankhurst 2005, Schmitz & Wainwright 2011). The biology underlying allometric patterns in eye size is not fully understood (Howland et al. 2004), but it appears that the high energetic cost of operating eyes and their associated neural structures discourages the development of eyes that are larger than necessary (Laughlin 2001). While nocturnal or deep-dwelling species clearly benefit from the light-gathering abilities of large eyes, for diurnal species the main potential advantage of larger eyes is greater acuity (Kiltie 2000). However, as fish grow they tend to eat progressively larger prey (Scharf et al. 2000), so high visual acuity may be redundant for adults.

Allometric relationships within a species can potentially vary in space and time, as relative eye size may either decrease when eyes shrink to accommodate enlarged gills or buccal cavities (Witte et al. 2008), or increase when eye growth is maintained at the expense of somatic growth under food limitation (Pankhurst 1992, Pankhurst & Montgomery 1994). Therefore, relationships between relative eye size and body length for a particular species should be applied cautiously to circumstances beyond those under which the measured specimens were collected (Pankhurst & Montgomery 1994, McDowall & Pankhurst 2005).

Using an allometric approach to length estimation enables the use of video systems that have only one camera and do not need a scale bar. This reduces the cost and physical size of the system and simplifies image processing relative to stereo photography. The low cost, small size and simplicity of such systems makes them amenable to use by low-budget research programmes or citizen scientists, who are playing an increasingly valuable role in the surveying and monitoring of fish populations (e.g. Edgar & Stuart-Smith 2009). Further, unobtrusive single cameras are less likely to generate biased counts if fish are attracted to or deterred by bulkier systems in the way that some species respond to divers (Cole 1994, Dickens et al. 2011).

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