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Review

Underwater video techniques for observing coastal marine biodiversity: A review of sixty years of publications (1952–2012)

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ABSTRACT

Underwater video techniques are increasingly used in marine ecology studies. Technological progress regarding video cameras, sensors (such as sounders), battery life and information storage make these techniques now accessible to a majority of users. However, diver-based underwater visual censuses, and catch and effort data, remain the most commonly used for observing coastal biodiversity and species. In this paper, we review the underwater video techniques that have been developed since the 1950s to investigate and/or monitor coastal biodiversity. Techniques such as remote underwater video, whether baited or not, diver-operated video and towed video are described, along with corresponding applications in the field. We then analyse the complementary of techniques, first from studies comparing video techniques with other observation techniques, whether video-based or not, and second by documenting their respective cost efficiencies. These findings are discussed with respect to current challenges in monitoring and investigating coastal biodiversity. Video should be more often considered and used, either in addition to or as an alternative to diver-based, fishing and acoustic techniques, as it may be particularly suited for monitoring coastal biodiversity in a variety of areas and on larger scales than hitherto and within an ecosystem-based approach to management and conservation.

Contents

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1. Introduction

The conservation of marine and coastal biodiversity and associated ecosystem services through ecosystem-based management (Christensen et al., 1996) requires appraising a wide array of biodiversity components on large spatial scales. Biodiversity here encompasses mostly fish and macroinvertebrate species, whether or not exploited, and corresponding assemblages and habitats. Biodiversity is rarely observed and assessed on such scales due to observation costs. The main techniques used to study and monitor biodiversity are either extractive (e.g. fishing, dredging), based on acoustics, or based on Underwater Visual Censuses (UVC).

Extractive techniques have been used mostly for fish, macrobenthic organisms and endogenous fauna, primarily for the assessment of fished populations. Fishing-based surveys (see e.g. Petitgas et al., 2009) focus on catchable species, whether or not exploited. The potential of catch-based surveys for an ecosystem approach to fisheries management has been addressed by Trenkel and Cotter (2009) and Jouffre et al. (2010), among others. Catch-based monitoring provides information about catchable species, but not on other species, nor on habitat. Catchability may vary across species and as a function of weather conditions (Trenkel and Cotter, 2009) and vessels (Pelletier, 1991). Sampling effort by fisheries is considerable, but data interpretation may be tricky due to the uncontrolled sampling design. Scientific catch surveys circumvent this problem, but provide small sample sizes compared to fisheries catch (Trenkel and Cotter, 2009). In addition, extractive techniques have an impact on biodiversity, which may not be desirable in the context of monitoring conservation strategies. Rotenone sampling is similar to fishing, in that it is extractive, focuses on fish species, and selects only part of the fish assemblage (Robertson and Smith-Vaniz, 2008). It is thus used more for inventories and small-scale observations than for monitoring. Underwater acoustics is currently effective for pelagic and semi-demersal species, and for zooplankton (Trenkel et al., 2011). However, species present in the acoustic data have to be identified through complementary techniques, and benthic species are not well-observed. For instance, Jones et al. (2012) combined acoustics and video to estimate rockfish biomass in untrawlable areas.

In shallow areas, UVC techniques have been used for over sixty years to monitor fish, macrobenthic organisms and habitats (Brock, 1954). They are considered to be reliable and cost effective (Thresher and Gunn, 1986). Advantages and disadvantages of UVC for estimating fish abundance and diversity have been reported and discussed in several papers (Chapman et al., 1974; Sale, 1980; Brock, 1982; Harmelin-Vivien et al., 1985; Watson et al., 1995; Thompson and Mapstone, 1997; Willis, 2001; Kulbicki et al., 2010; Dickens et al., 2011). The main limitation of UVC lies in the need for divers' presence underwater, which influences the observation of vagile macrofauna, restricts the number of observations that can be carried out, and constrains depth observation.

In recent years, underwater video techniques have been increasingly used for observing macrofauna and habitat in marine ecosystems (see e.g. Sarradin et al., 2007 for a review concerning deep ecosystems). Technological progress regarding video cameras, sensors (such as sounders), battery life and information storage now make these techniques accessible to the majority of users. The term "underwater video" encompasses an array of techniques developed around the world, and used in a variety of contexts and for different purposes. Murphy and Jenkins (2010) reviewed the observation methods used for spatial monitoring of fish and associated habitats. They summarized the applications, advantages and shortcomings of all methods used, including UVC, remote sensing, acoustics, experimental catch and effort data, and underwater video. Because of this broad scope, the paper did not document the various video techniques and their applications. To our knowledge, there are no published papers describing underwater video techniques and their applications, and discussing their respective relevance for observing shallow water marine biodiversity. Yet many papers have been published using video techniques in this context, and video-based techniques have considerably evolved over time. The present review focuses on the video techniques developed and used for this purpose, from the first published papers through to 2012. Section 2 describes the main techniques, along with technological issues. Applications of each technique are summarized in section 3. In section 4, studies comparing video techniques with other observation techniques are listed, and their conclusions are summarized. The last section discusses the potential of video techniques for monitoring and investigating biodiversity issues in coastal environments, in order to provide guidance in choosing among techniques.

2. State of the art regarding underwater video techniques

Literature searches were conducted using the ISIS Web of Knowledge^{SM} and Google Scholar for relevant keywords, including "underwater video", "underwater television", "remote underwater video", "baited video", "BRUV", "towed video", "video transect" and "stereo-video". In addition to database searches, we also hand-checked the reference lists of all studies retrieved to identify all relevant primary research published in peer-reviewed journals, books and proceedings of international conferences. Thus a substantial amount of grey literature was not taken into account in this review.

We restricted the literature search to environments shallower than 100 m. At greater depths, observations are more constrained by technological issues, scuba diving is not routinely feasible, and artificial light is needed. Papers pertaining to freshwater ecosystems were not included in the review either. Studies using photography, photogrammetry, underwater video for evaluating fishing gear catchability or acoustic techniques, and video tracking (Delcourt et al., 2012) fell outside the scope of the paper. The search resulted in a list of 182 peer-reviewed papers, taking into account the majority of peer-reviewed papers within the scope of the present review. As video systems are increasingly used around the world, the number of published studies has greatly increased over the last decade (67% of the papers were published from 2002 onwards). Papers were sorted according to four main techniques:

remote underwater video, baited remote underwater video, towed video and diver-operated video. Note that the term "remote" is used here to designate a technique which does not require human presence underwater, while the term "autonomous" indicates a system that is not linked to a vessel or a platform. Baited Remote Underwater Video will be denoted BRUV following most studies using this technique, while unbaited Remote Underwater Video will be simply termed RUV for the sake of concision. RUV thus includes here all remote video systems that are not baited, whether dropped from the boat or set by divers. Note that trademarks on "BRUVS" and "RUVS" of the Australian Institute of Marine Science were not used as they are too specific and do not encompass all the techniques discussed in this review.

2.1. Remote underwater video (RUV)

The first published work reporting the use of underwater video systems in the coastal environment dates back to the 1950s.The Scottish Marine Biological Association of Millport developed an underwater video program in 1948, and tested it in the Aquarium of the Zoological Society of London in 1949 (Barnes, 1952, 1953). In 1951, the Royal Navy constructed a system which was successfully used to identify a Royal Navy submarine lost at sea in 1951. It then served for other projects on bottom fauna (Barnes, 1955) as suspended in a mid-water environment (Backus and Barnes, 1957) and for other Navy applications (Barnes, 1963). RUV has used more frequently in marine sciences since the 1960s (Table 1). It provided the first data on fish movement and behaviour in daytime and at night, which had not been previously studied without human disturbance (Barnes, 1952; Kumpf and Lowenstein, 1962; Booda, 1966; LaFond, 1968). RUV systems exhibit different designs and technical features, including additional sensors, and can be distinguished in terms of their autonomy (linked or autonomous).

2.1.1. Linked systems

The system developed by LaFond et al. (1961) filmed from the surface to the bottom (20 m depth) while moving up and down a vertical-rail track placed under a platform (Table 1). It was used to study diurnal and nocturnal fish movements along with plankton dispersion (see section 3). Over the same period of time, an experimental RUV equipped with hydrophones and lights for night vision (AC-RUV, "AC" for acoustic) was developed by Kumpf and Lowenstein (1962) and Kronengold et al. (1964). The system was permanently set on sea bottom in the Bahamas (Steinberg and Koczy, 1964), in order to (i) identify the sounds present in a supposedly silent environment; (ii) learn about wildlife behavioural response to sound disturbance; (iii) describe the temporal patterns of sounds, and (iv) evaluate the advantages and limitations of systems coupling video and acoustics. Initial problems resulting from a large system size and from fouling on the camera housing led to an improved smaller AC-RUV system (Holt, 1967; Stevenson, 1967; Table 1).

More recently, Stokesbury et al. (2004) developed a vertical RUV system (Table 1) to study scallop distribution off the northeastern coast of the United States. Tyne et al. (2010) used the same system to record benthic habitats in Western Australia. The camera filmed a 1 m^2 bottom quadrat area at depths ranging between 2 and 16 m. Recorded images were automatically analysed by a computer, providing estimates of the percent seagrass cover, and the type and abundance of sponges within the quadrat.

The latest linked systems are permanent observatories using cables for energy supply, data transfer and instrument control (Aguzzi et al., 2012). In an area south of Taiwan, Jan et al. (2007) placed a system linked to an internet video server, making the videos viewable in real time on the World Wide Web. In the western Mediterranean, Aguzzi et al. (2011) set the OBSEA system at 20 m depth to monitor fish assemblages (Table 1).

2.1.2. Autonomous systems

Fedra and Machan (1979) used the first autonomous RUV in the North Adriatic Sea (Mediterranean) (Table 1). The system was set on the seabed by a diver and then left for a week, in order to study the behaviour and distribution of benthic and demersal species, their feeding activities and movement patterns, along with species interactions and the influence of environmental conditions (see section 3). Chabanet et al. (2012) recently introduced a similar system to investigate the temporal variability of undisturbed fish populations over a twenty day time period. Dunbrack and Zielinski (2003) devised a system with a camera mounted on a tripod. It was placed at the edge of the reef slope to film down the reef and study the ecology, behaviour and population status of the bluntnose sixgill shark (*Hexanchus griseus*) in the Georgia Strait, British Columbia (see also Dunbrack, 2006, 2008).

The rotating RUV system (ROT-RUV: "ROT" for rotation, termed "STAVIRO" by the authors) of Pelletier et al. (2012) (Table 1) is fixed on a tripod, dropped from the boat onto the seabed, and retrieved using buoys and rigging. It has been used in the New Caledonian lagoon (South Pacific) since 2007 and in the Western Mediterranean since 2010 to study and monitor the spatio-temporal distribution of marine macrofauna and habitat (Pelletier et al., 2012; D. Mallet, M. Bouchoucha, D. Pelletier, unpublished data). Unlike other RUV systems, the 360° view afforded by rotation provides panoramic images and a much larger surveyed area than fixed systems, while avoiding the image distortion characteristic of fisheye lenses. Potential double counting is minimized by paying particular attention to the direction of fish movement with respect to rotation, and by calculating the mean abundance over rotations, to average out the variability between rotations (Pelletier et al., 2012).

Most of the above techniques were implemented with the help of divers, except for Stokesbury et al. (2004), Tyne et al. (2010) and Pelletier et al. (2012). Only four RUV techniques identified in this review did not use artificial light (Stevenson, 1967; Petrell et al., 1997; Dunbrack and Zielinski, 2003; Pelletier et al., 2012).

Video systems remaining underwater for several days inevitably face the problem of fouling, i.e. the accumulation of organisms, impairing the quality of images. Yet in the literature examined, this problem was raised and addressed only by Stevenson (1967) and Chabanet et al. (2012), who used automatic windshield wipers to clean the lens surface regularly.

2.2. Baited remote underwater video (BRUV)

A BRUV system uses either a single camera or two cameras (see subsection 2.5) filming the area surrounding a bait used to attract fish. The bait bag is placed close to the camera, at a distance ranging between 0.5 m and 1.5 m (Ellis and DeMartini, 1995; Willis and Babcock, 2000; Heagney et al., 2007). The species attracted and the bait range of action depend on the bait used (Harvey et al., 2007; Stobart et al., 2007; Wraith, 2007). Pilchards (*Sardinops* sp.) are currently used in most studies (Mclean et al., 2010, 2011; Watson et al., 2010; Bassett and Montgomery, 2011; Goetze et al., 2011; Harvey et al., 2012a; Langlois et al., 2012a,b). BRUV systems are directly deployed from the boat (Watson et al., 2005; Cappo et al., 2007a; Bassett and Montgomery, 2011). Willis and Babcock (2000) and Watson et al. (2005) showed that a soak time of 25–40 min underwater was required to obtain representative observations for the majority of fish species, but they recommended a duration of 50–60 min for observing most target fish species in the census. The main differences among BRUV systems concern the orientation of

Table 1
Technical specifications of unbaited RUV systems. Horizontal (H) and vertical (V) in the second column refer to the direction of image recording.

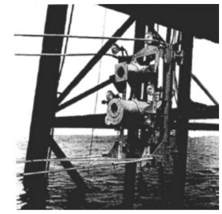
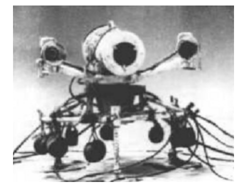
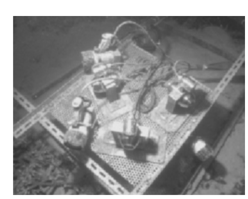
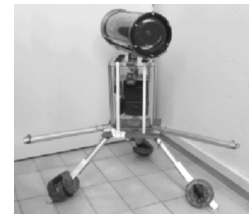
Source	Type	Technical details	Illustration
LaFond et al. (1961)	H-RUV	Mounted on a vertical rail Linked to mobile platform Additional equipment: six floodlights	
Kumpf and Lowenstein (1962), Kronengold et al. (1964)	AC-H-RUV	Linked to laboratory control panel by a multi-conductor cable. Observation duration: 24 h Lens view angle: wide 2 spotlights, hydrophones, sound projector	
Stevenson (1967), Holt (1967)	AC-HV-RUV	Linked to laboratory control panel Energy supplied through a submarine cable Observation duration: 24 h Pan tilt mechanism (360° horizontally and 50° vertically), lens view angle: wide Remotely controlled windshield-wiper, releasing a toxic material, hydrophones, sound projector	
Fedra and Machan (1979)	H-RUV	Autonomous Observation duration: 1 week Lens view angle: wide Side flash reflectors (12 V battery in separate housing), Electronic timer (6V batteries)	
Dunbrack and Zielinski (2003)	V-RUV	Autonomous Observation duration: 240 h (20 days) Black & white camera, electronic timer Additional time-lapse video recorder	NA
Stokesbury et al. (2004) and Tyne et al. (2010)	V-RUV	Downward-oriented video camera, attached to the apex of a stainless steel pyramid Linked to boat Black & white camera linked to a laptop computer Additional infrared illumination	
Jan et al. (2007)	H-RUV	Linked to laboratory, internet video streaming Continuous recording: Colour camera Additional illumination for night time	
Aguzzi et al. (2011), Condal et al. (2012)	H-RUV	Linked to laboratory, transmission of audio and video for internet streaming Pan tilt mechanism (360° horizontally and 210° vertically)	NA

Table 1 (*Continued*)

Source	Type	Technical details	Illustration
Pelletier et al. (2012)	ROT-H-RUV	2 waterproof housings connected by an axis. Engine lower housing sets in motion the upper housing Programmed rotations of 60° every 30 seconds Autonomous Observation duration: 9 min (i.e. 3 rotations) Colour HD camera, Lens view angle: 60°	

the system in relation to the sea bottom (horizontal or vertical, Table 2), which result in distinct observed abundances and species compositions (Langlois et al., 2006; Wraith, 2007). BRUV has also been used with infrared light to study nocturnal fish; for example Bassett and Montgomery (2011) studied the olfactory capabilities of nocturnal fish species and their influence on response to bait using this system.

2.2.1. Horizontally oriented BRUV

Horizontal BRUV (H-BRUV) (Ellis and DeMartini, 1995) provides a wide viewing angle for observing the area surrounding the bait. An array of species can be observed, in particular those not approaching the bait bag because of fish behaviour or competition for the bait (Cappo et al., 2004; Harvey et al., 2007). H-BRUV systems have been mainly used to study spatio-temporal variations in reef fish assemblages, the influence of depth and location upon fish and species distribution, and the effect of MPAs on biodiversity (Cappo et al., 2007b and section 3). H-BRUVs are generally set on the seafloor, though Heagney et al. (2007) used mid-water BRUV to study pelagic fish.

2.2.2. Vertically oriented BRUV

Vertical BRUV (V-BRUV) has been used for studying the size and abundance of carnivorous fish (Babcock et al., 1999; Willis and Babcock, 2000) and the effect of protection by MPAs (Willis et al., 2000, 2003; Denny and Babcock, 2004; Denny et al., 2004; Willis and Millar, 2005). The restricted field of vision due to the camera pointing downwards ensures a constant field of view and a constant focal length, particularly where water clarity or topography varies between observations (T. Willis, personal communication). Langlois et al. (2006) suggested that some species would rarely approach the system when the camera was positioned above the bait. Other authors suggested that recent V-BRUV does not affect blue cod and various other species (T. Willis, personal communication). Lightweight stands have been shown to provide precise relative density estimates of carnivorous fishes (Willis et al., 2000).

2.3. TOWed Video (TOWV)

Machan and Fedra (1975) introduced the first TOWed Video technique (TOWV) in shallow waters. The system was towed by

Table 2
Technical specifications of Baited RUV systems. Horizontal (H) and vertical (V) in the second column refer to the direction of image recording.

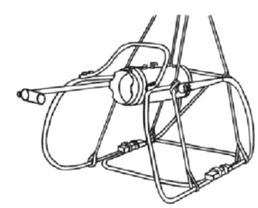
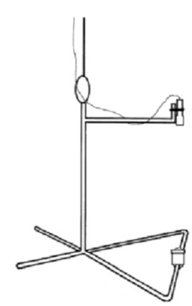
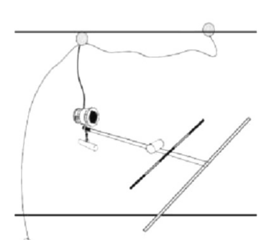
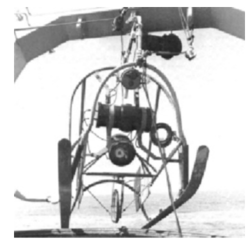
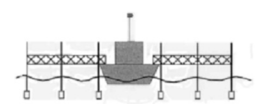
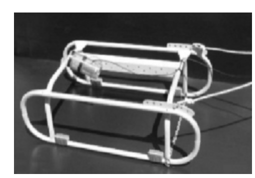
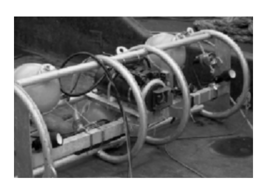
Source	Type	Technical details	Illustration
Ellis and DeMartini (1995)	H-BRUV	Autonomous Set on bottom Observation duration: 10 to 60 min Colour camera (red filter for underwater vision) Lens view angle: wide No additional sensors	
Willis and Babcock (2000)	V-BRUV	Linked to boat Observation duration: 30 or 60 min Colour camera	
Heagney et al. (2007)	Mid-water H-BRUV	Autonomous Mid-water device Observation duration: 45 min Lens view angle: wide Depth sounder	

Table 3
Technical specifications of Towed video systems (TOWV). Camera orientation is reported in the third column.

Source	Type	Technical details	Illustration
Machan and Fedra (1975)	Seabed TOWV	Angled down (30°) Linked to boat Boat speed: max 1 m s^{-1} Observation distance: 20 km in 1 day Still camera, spotlight, flash	
Holme and Barrett (1977)	Seabed TOWV	Angled down (45°) Linked to boat Boat speed: (1/2)–1 knot (0.257–0.514 m s^{-1}) Transect length: around 3.5 km Observation duration: 2.5 h (max 3 h) Still camera, light	
Norris et al. (1997)	Mid-Water TOWV	Angled down Linked to boat Boat speed: max 1 m s^{-1} Transect length: 174 m Observation duration: 183 s Colour camera Additional light	NA
Riegl et al. (2001)	Mid-Water TOWV	Vertical The video cameras were individually linked to six onboard recorders Transect length: 50 m Colour camera Lens view angle: wide	
Spencer et al. (2005)	Seabed TOWV	Vertical Linked to boat Boat speed: 0.6 m s^{-1} Transect length: 30, 100, and 200 m Observation duration: 2 h Black & white camera Lens view angle: field of view = 5 m^2 Temperature sensor	
Hayashizaki and Ogawa (2006)	Mid-Water TOWV	Vertical Linked to boat Transect length: 50 m GPS, depth sounder	NA
Rooper and Zimmermann (2007)	Seabed TOWV	Angled down (35°) Linked to boat Boat speed:1.8–2.7 km h^{-1} Observation duration: 45–55 min Colour camera Three lasers, lights	

a vessel at low speed (0.1–1 m s^{-1}). TOWV films along a transect of predefined size and trajectory (30 m to 20 km). The various systems developed (Table 3) were linked to the vessel by a coaxial cable and a rope. The main difference among them lies in the position at which the system operates in the water column, i.e. seabed or mid-water.

2.3.1. *Seabed TOWV*

In the coastal domain, the first TOWV systems were towed on the seabed using a sledge (seabed-TOWV, Table 3). These were used in the Mediterranean Sea (Machan and Fedra, 1975), in South-West England (Holme and Barrett, 1977) and in Alaska (Spencer et al., 2005, and Rooper and Zimmermann, 2007). The video camera is slightly angled downwards on the sledge, which carries additional equipment (Table 3). Seabed-TOWVs have been used to study sea floor and epifaunal species (mostly crustaceans and flat fish) (see section 3). It should be noted that in shallow waters such as lagoon areas, vagile species were found to be sensitive to the boat noise (D. Pelletier and G. Hervé, unpublished data).

2.3.2. *Mid-water-TOWV*

Mid-water-TOWV systems are more recent than seabed-TOWVs in shallow waters (Norris et al., 1997). These systems are towed at a constant elevation in the water column, thus providing a wider view of the seafloor compared to seabed-TOWVs. The system of Riegl et al. (2001) is set on each side of the boat with vertical tubes

Table 4
Referenced studies involving DOV, with main protocol features, and study focus. For comparison, Bortone et al. (1991, 1994) presented the stationary rotating point count technique for counting fish, with an observation radius of 5.64 m (see text for details). ST: straight transect; TC: time census; TT: towed transect; BT: browsed transect.

Source	Census type	Length (m)	Distance above the bottom (cm)	Speed ($m\,s^{-1}$)	Study fish/habitat
Alevizon and Brooks (1975)	ST	50	NA	NA	Fish
Davis and Anderson (1989)	ST	200	100	0.33	Fish
Greene and Alevizon (1989)	ST	NA	NA	Constant	Fish
Leonard and Clark (1993)	ST	2	50	0.07	Habitat
Aronson et al. (1994)	ST	25	NA	Slowly	Fish & Habitat
Parker et al. (1994)	TC (15 min)	NA	100	With prevailing current	Fish
Carleton and Done (1995)	TT	200	100–150	1–1.23	Habitat
	ST	200	100–150	0.63–0.78	Habitat
Vogt et al. (1997)	TT	500	50–70	0.11–0.25	Habitat
Ninio et al. (2000)	ST	50	25–30	NA	Habitat
Rogers and Miller (2001)	ST	20 and 100	40	0.03	Habitat
Ninio et al. (2003)	ST	50	25–30	NA	Fish & Habitat
Tessier (2005), Tessier et al. (2005)	ST	24	300	0.3	Fish
Watson et al. (2005)	ST	25	NA	NA	Fish & Habitat
Houk and Van Woesik (2006)	ST	15, 35 and 50	NA	0.15	Habitat
Kenyon et al. (2006)	TT	19.2 to 38.6	100	0.69–0.97	Habitat
Lam et al. (2006)	ST	50	40	0.10	Habitat
Leujak and Ormond (2007)	ST	50	30–35	0.12	Habitat
Cruz et al. (2008)	ST	20	40	0.05	Habitat
Langlois et al. (2010)	ST	25	30	3	Fish & Habitat
Watson et al. (2010)	ST	50 and 100	30	0.34	Fish & Habitat
Pelletier et al. (2011)	ST	50	150	0.2–0.3	Fish
	BT	50 × 4	Varying elevation	Speed	Fish

that can be lowered or raised between 0.5 and 3.5 m below the sea surface, so as to adjust to varying depth (Table 3). Most mid-water-TOWVs are equipped with a depth sounder (Hayashizaki and Ogawa, 2006; see also Schaner et al., 2009, for a freshwater application). They have mostly been used to characterize, quantify and assess changes in benthic flora (seagrass, macro-algae and coral) and fauna.

2.4. Diver-operated video (DOV)

The diver-operated video technique (DOV) consists of a diver holding a video system and filming a defined area. Similarly to UVC, the observation area may vary in size (transects from 2 to 500 m, Table 4) and shape (along a predefined line, inside a quadrat, or rotating around a fixed point). The diver is sometimes towed (Carleton and Done, 1995; Vogt et al., 1997; Kenyon et al., 2006), recalling the “Manta tow” technique, where a towed snorkeler implements a transect (Fernandes, 1990). Towed DOV has been used to record benthic habitat along long transects (up to 500 m long).

The DOV technique (Alevizon and Brooks, 1975) involves a diver filming vertically along a transect line. DOV is generally conducted at a constant swimming speed over the entire transect (0.1–3 $m\,s^{-1}$, Table 4). Elevation above the seafloor ranges from 0.15 to 0.5 m (parameter documented in 16 papers out of 22). But in some cases, transects are conducted at a larger elevation (1–3 m) to ensure a wider viewing angle (Table 4). A reference bar attached to the camera housing is sometimes used to control the camera elevation (Leonard and Clark, 1993; Vogt et al., 1997; Rogers and Miller, 2001; Lam et al., 2006; Cruz et al., 2008).

Pelletier et al. (2011) presented the browsing video transect technique, where the diver browses inside the strip transect area, at varying elevation, speed and angle, and zooming when needed. This technique mimics the behaviour of UVC divers in strip transects. These authors demonstrated that more individuals and species were recorded from browsing transects than from straight ones conducted at a constant elevation.

Bortone et al. (1991, 1994) proposed a protocol where the diver simultaneously rotates and records images, mimicking the UVC stationary point count technique (Bohnsack and Bannerot, 1986). DOV was also used to study fish behaviour by Krohn and Boisclair (1994) (energy expenditure of swimming fish) and Hall and Hanlon (2002) (observation of particular individuals for up to 1.5 h)

2.5. Stereo-video technique

The stereo-video technique is not additional to those described above, but it involves a particular recording that produces a 3-dimensional (3D) image. It was developed by Harvey and Shortis (1995) to improve fish size estimation by divers. The technique simultaneously uses two cameras to record the same scene. Left and right images are synchronized on the computer based on a light-emitting diode (LED) placed at 2.5 m from the cameras and seen on both images. Images are then cross-checked from ad hoc software to obtain a 3D image allowing individual size measurement. A 1.4 m distance between the two cameras was found to provide a trade-off between the precision afforded by a greater distance and diver's ability to manoeuvre the system (Harvey and Shortis, 1995). This system recorded and measured individuals in a distance range of 2–10 m, depending on underwater visibility. Length measurements were found to be more accurate and repeatable when the orientation of the subjects to the stereo-cameras was less than 50° (Harvey and Shortis, 1995, 1998). Stereo-video has been shown to provide more accurate estimates of both fish length and distance than visual estimation by divers (Harvey et al., 2001a,b, 2002a, 2004) or single video (Harvey et al., 2002b). As such, it also helps distinguishing individuals (Harvey et al., 2003, 2007).

The stereo system has been adapted to all underwater video techniques (RUV and BRUV, TOWV, and DOV), but it has been mostly implemented on H-BRUV systems (Watson et al., 2007, 2009; Chatfield et al., 2010; Mclean et al., 2010, 2011; Goetze et al., 2011; Birt et al., 2012; Dorman et al., 2012; Fitzpatrick et al., 2012; Harvey et al., 2012a,b,c; Langlois et al., 2012a,b). Several comparisons of underwater observation techniques used stereo-video (Watson et al., 2005, 2010; Langlois et al., 2010). Shortis et al. (2009) provide a detailed review of the status of underwater stereo-video measurement and marine and ecology applications. With the same objective of measuring fish, Heppell et al. (2012) used two lasers fixed on each side of a single camera, rather than stereo-video.

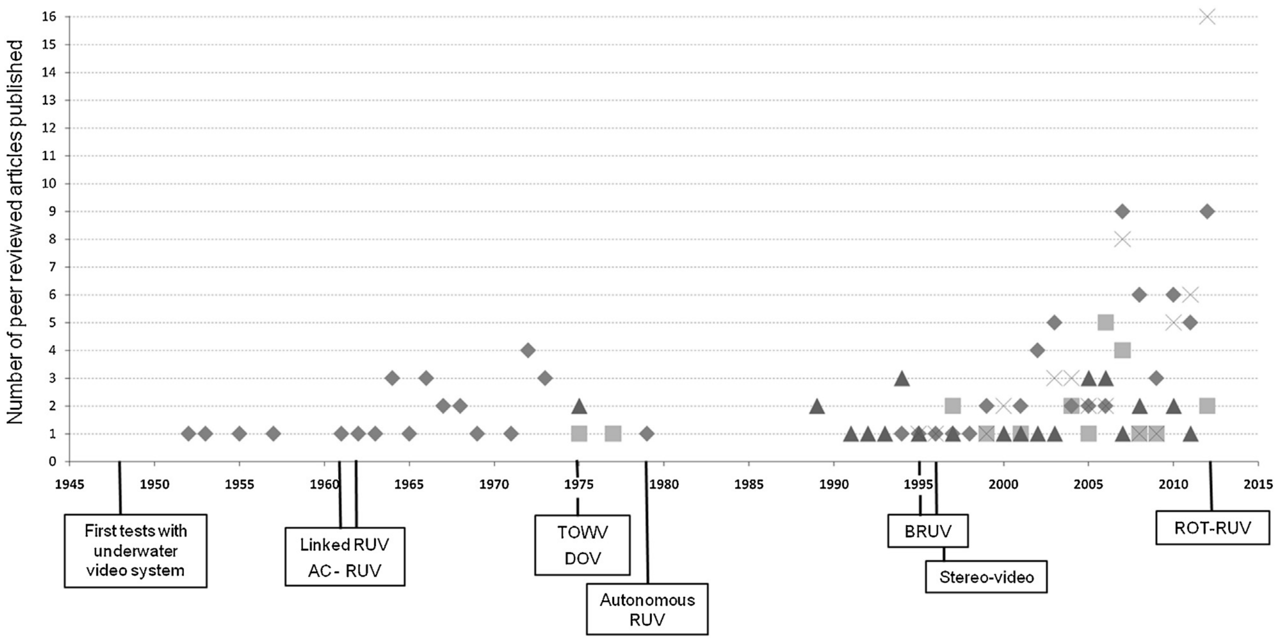


Fig. 1. Historical perspective on the development of underwater video systems, with associated papers (♦ RUV; ■ TOWV; ▲ DOV; X BRUV).

2.6. Technological progress

The first video systems used (Barnes, 1952, 1953, 1955; Backus and Barnes, 1957; Myrberg et al., 1969; Myrberg, 1973) suffered from (i) difficulties in setting and retrieving systems; (ii) malfunctioning of electronically driven systems; and (iii) the limitations of video sensors which severely impaired image quality.

Various systems have been developed and used over time (Fig. 1). The emergence and evolution of such systems was primarily driven by technological progress, enabling considerable improvements in performance, while making these tools more robust, smaller and cheaper. The digital revolution led to increased sensor resolution, with a dramatically improved image quality, in particular with the advent of High Definition (HD). Regarding energy supply, batteries have become smaller and more powerful. Data storage devices now make it possible to record and archive more images, since camera internal memory or Secure Digital (SD) cards can now store up to 120 Gigabytes (GB), while the capacity of standard external hard drives is 1 or 2 Terabyte (TB). The increasing volume of observation files is therefore matched by a corresponding increase in information storage capacities.

3. Underwater video: where is it used and what is it used for?

Video systems are increasingly used around the world, particularly over the last decade (Fig. 1). Nevertheless, there are not many teams using these techniques. Numerous studies have been published in Australia (63 papers from 1995 to 2012), the USA (24 papers from 1957 to 2012) and New Zealand (24 papers from 1995 to 2011), and in comparison, relatively few papers from other countries (Fig. 2 and Supplementary Material A). The first publications on RUV systems originated in Europe (United Kingdom in 1952) and North America (USA in 1957), and then extended to all continents (Oceania in 1995, Asia in 1997 and Africa in 2008). Twenty papers were published from the Bahamas AC-RUV between 1962 and 1973. BRUV has mainly been used in Australia since 2003 (32 of the 52 BRUV-based papers), and in New Zealand since 1999 (11 papers). In Australia only H-BRUV has been used, whereas in New Zealand V-BRUV has mostly been used (9 of the 11 BRUV-based papers). Studies involving TOWV and DOV are both more widespread and less numerous, with respectively 23 and 28 papers published since 1975. Note that the grey literature and studies outside the scope of this review (deep environment and freshwater) contain a large amount of work which has not been cited here (including some of the authors' work).

The techniques described in the previous section have been used for a variety of purposes in the context of coastal biodiversity. Applications were classified according to five main subjects (Table 5) to provide an overview. Studies of animal behaviour and activity are a major field of application (52 references published between 1952 and 2012). Six papers used video to investigate the effect of human-induced disturbances upon species behaviour. Forty-eight papers investigate spatial and temporal patterns of fish abundance, size and of fish assemblage composition, in particular to appraise the effects of habitat, anthropogenic pressures and MPAs. Thirty-two references dealt with habitat mapping and benthic cover monitoring, but benthos monitoring at species level was addressed by only four references. Not surprisingly, video techniques have been specialized, depending on these areas of application. RUV has been preferably used for behaviour-related studies (45 references), and only recently become of interest for assessing species response to environmental conditions and habitat through spatially-replicated designs (8 references from 2008). In contrast, BRUV has been extensively used for this latter purpose (25 references), with an emphasis on size estimation through stereo-video, whereas it has been hardly used for behavioural studies. TOWV has been almost exclusively used for habitat mapping and monitoring purposes (15 references); studies mostly focused on benthic macrofauna (e.g. coral cover and scallops) and macroflora (e.g. sea grass and algae), though some examined demersal fish species. DOV has also been used for assessing fish abundance and assemblages (13 references), habitat mapping and monitoring (15 references), and investigating fish behaviour (2 references). It is important to note that each technique was tested in both temperate and tropical ecosystems. It should also be underlined that Table 5 provides an average picture over the review period. Technological progress entails new observation capacities, and therefore new fields of investigation, such as exemplified by recent applications of RUV to fish and habitat monitoring. In addition to these applications, the great potential of video for

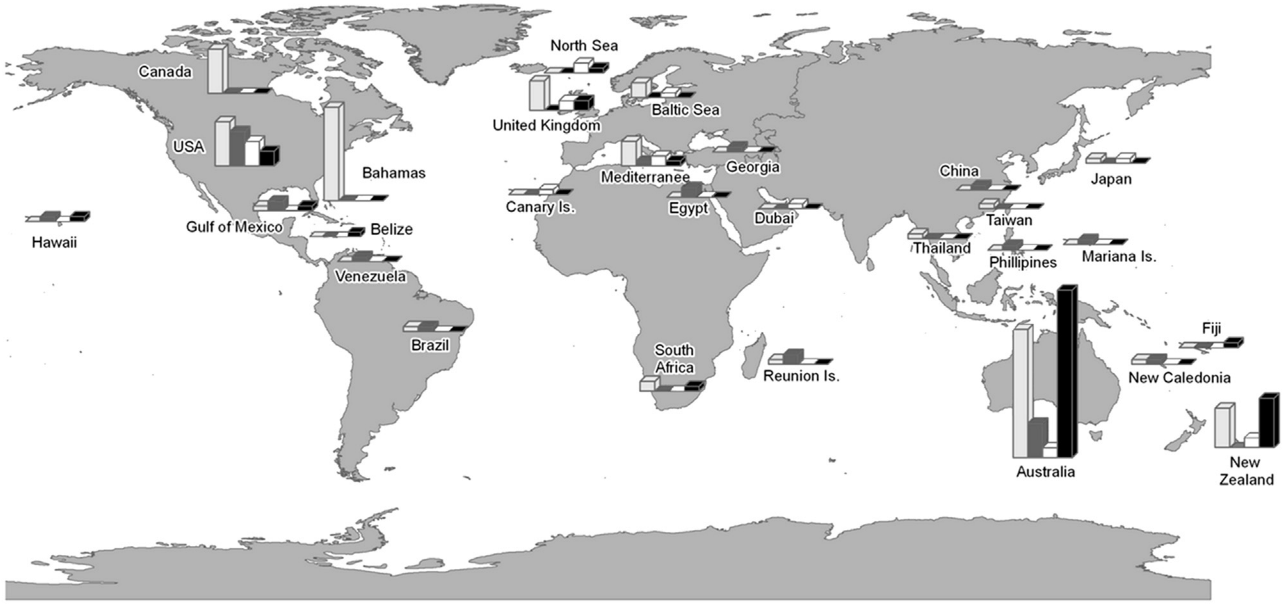


Fig. 2. Geographical distribution of published studies. Each bar is proportional to the number of papers published for each technique: ▭ RUV; ▭ DOV; ▭ TOWV and ▭ BRUV. The number of papers published by year and country per technique are given in Supplementary Material A.

addressing specific biodiversity-related topics was also illustrated by unusual applications, e.g. seals in underwater caves (Dendrinos et al., 2007).

Lastly, attention was paid to the kind of information collected by each technique. Fish species are most often identified at the lowest possible taxonomic level, notwithstanding a small fraction of individuals, in general small species, identified only at higher levels such as genus or family (see e.g. Pelletier et al., 2011). This must be taken into account when calculating metrics based on species counts. In some instances, metrics may only be calculated at genus or family level. In general, epifauna and epiflora are identified according to broad categories, e.g. sponges (Tyne et al., 2010), macroalgae (Bucas et al., 2007), tunicates and ophiuroids (Carbines and Cole, 2009). Benthos and habitat are generally characterized through percent covers of the sea bottom. In all cases, the species that can be observed in a reliable way must be carefully listed. Cryptic species are poorly observed and the limitations of visual counts due to underwater visibility are also valid for video techniques. Small species may be more difficult to identify from video images than from visual counts, whereas diver-avoiding species are more likely observed from diver-free video systems (Mallet et al., 2014).

A large number of metrics can then be obtained from all the techniques (Table 6). Species are counted over the observation duration to provide presence/absence, occurrences and species richness. In the case of vagile species, abundance is estimated over the whole video sequence or part of it for RUV, DOV and TOWV. In contrast, for BRUV the metric used is the time of first appearance per species (Wraith, 2007), and most often MaxN, the maximum abundance per species seen over the observation period (Ellis and DeMartini, 1995). MaxN is a conservative estimate of abundance (Willis et al., 2000). Bacheler et al. (2013) proposed using the mean number of fish observed in a series of snapshots over a viewing interval (MeanCount). Schobernd et al. (2013) compared MaxN and MeanCount from simulations, laboratory experiment and modelling. They found that MeanCount was generally linearly related to true abundance with a variability similar to MaxN. Fixed species and habitat are quantified either through abundance or percent cover. Estimating the size of individuals is generally done using stereo-video. Counts may also be assigned to size classes to avoid the issue of size estimation. Lastly, depending on the way cameras are set, video may allow other metrics to be considered, such as the number of bites from herbivores, the occurrence of activities, or parameters describing habitat (Table 6).

4. Complementarity of techniques

4.1. Comparative studies

From our literature search, we identified forty-two papers comparing two or more observation techniques (Table 7). More than 65% (28 out of 42) of papers compared UVC with a video technique: RUV (5 papers), TOWV (3), DOV (8), BRUV (9), and stereo-RUV (5). As video is perceived as a relatively new observation technique, it was often compared to UVC, which is commonly used for observing fish communities and habitats in shallow areas. Other comparisons involved two or more video techniques for (i) testing the effect of using two cameras compared to a mono-camera (stereo-RUV versus RUV); (ii) testing the effect of baiting (BRUV versus RUV); and (iii) evaluating their respective relevance for studying reef fish assemblages (BRUV versus TOWV, stereo-RUV versus stereo-DOV, stereo-BRUV and stereo-DOV). Finally, several papers compared underwater video with, on the one hand, experimental fishing (two papers dealing with RUV, five with BRUV, two with stereo-BRUV and one with TOWV) and, on the other, acoustic techniques (one paper about BRUV).

Comparisons always used metrics based on species counts (species richness, taxonomic diversity, and frequency of occurrence), and on abundance estimates (Table 8). Note that each study presented a number of distinct results, which may vary across taxa and across environmental settings. Hence, although some techniques may have been compared using the same metric in several studies, conclusions might differ from one study to another. For instance, in some studies greater fish diversity was recorded with BRUV than with DOV (Langlois et al., 2010), TOWV and SRUV (Watson et al., 2005), and UVC (Willis and Babcock, 2000), while others show that more fish species were detected with UVC than with BRUV (Tessier et al., 2005; Langlois et al., 2006; Stobart et al., 2007; Colton and Swearer, 2010; Lowry et al., 2012) and DOV (Greene and Alevizon, 1989; Pelletier et al., 2011). In general, differences in observed abundances between techniques also depend

Table 5
Applications of underwater video techniques according to five main topics. NR indicates that No reference was found in the literature search.

	RUV	BRUV	TOWV	DOV
Natural behaviour and activity patterns (e.g. circadian)	Kumpf (1964), Steinberg and Koczy (1964), Steinberg et al. (1965), Cummings et al. (1966), Stevenson and Myrberg (1966), Stevenson (1967), LaFond (1968), Richard (1968), Myrberg et al. (1969), Colin (1971,1972,1973), Myrberg (1972a, 1972b), Myrberg and Spires (1972), Smith and Tyler (1973), Fedra and Machan (1979), Dunlap and Pawlik (1996), Barans et al. (2002, 2005), Bellwood et al. (2003), Dunbrack and Zielinski (2003), Jenkins et al. (2004), Bellwood et al. (2006), Dendrinos et al. (2007), Enstipp et al. (2007), Fischer et al. (2007), Fox and Bellwood (2007), Mantyka and Bellwood (2007a, 2007b), Bellwood and Fulton (2008), Fox and Bellwood (2008a), Meynecke et al. (2008), Cvitanovic and Bellwood (2009), Hoey and Bellwood (2009), Hoey (2010), Hoey and Bellwood (2010, 2011), Bennett and Bellwood (2011), Burkepile and Hay (2011), Lefèvre and Bellwood (2011), Burge et al. (2012), Hannah and Jones (2012), Masuda et al. (2012), Vergés et al. (2012)	Burrows et al. (1999), Bond et al. (2012), Burge et al. (2012)	Bräger et al. (1999), Grabowski et al. (2012)	Krohn and Boisclair (1994), Hall and Hanlon (2002)
Effect of human-induced disturbance on species behaviour (diver, bait, acoustics)	Dearden et al. (2010), Watson and Harvey (2007), Picciulin et al. (2010)	Watson and Harvey (2007), Dorman et al. (2012), Langlois et al. (2012b), Young and Bellwood (2012)	NR	NR
Spatial and temporal patterns of abundance, size and fish assemblage composition (including effects of habitat, anthropogenic pressures and protection)	Dunbrack (2008), Becker et al. (2010), Aguzzi et al. (2011), Bloomfield et al. (2012), Burge et al. (2012), Chabanet et al. (2012), Condal et al. (2012), Pelletier et al. (2012)	Willis and Babcock (2000), Willis et al. (2000, 2003), Denny and Babcock (2004), Denny et al. (2004), Cappo et al. (2007a), Malcolm et al. (2007), Stobart et al. (2007), Wraith (2007), Stoner et al. (2008), Gomelyuk (2009), Watson et al. (2009), Chatfield et al. (2010), Mclean et al. (2010, 2011), Cappo et al. (2011), Goetze et al. (2011), Lowry et al. (2011), Martinez et al. (2011), Birt et al. (2012), Fitzpatrick et al. (2012), Gladstone et al. (2012), Harvey et al. (2012a,b), Schultz et al. (2012)	Shucksmith et al. (2006), Carbines and Cole (2009)	Alevizon and Brooks (1975), Davis and Anderson (1989), Greene and Alevizon (1989), Aronson et al. (1994), Bortone et al. (1991, 1994), Parker et al. (1994), Ninio et al. (2000), Tessier et al. (2005), Watson et al. (2005, 2010), Langlois et al. (2010), Pelletier et al. (2011)
Benthos abundance and size monitoring	Handley et al. (2003), Dunbrack (2006)	NR	Holme and Barrett (1977), Spencer et al. (2005)	NR
Habitat mapping, Benthic cover monitoring and impact of fishing gears on habitat	Tyne et al. (2010), Pelletier et al. (2012)	NR	Machan and Fedra (1975), Holme and Barrett (1977), Norris et al. (1997), Riegl et al. (2001), Rosenkranz and Byersdorfer (2004), Spencer et al. (2005), Hayashizaki and Ogawa (2006), McDonald et al. (2006), Bucas et al. (2007), Rooper and Zimmermann (2007), Smith et al. (2007), Grizzle et al. (2008), Carbines and Cole (2009), Buhl-Mortensen et al. (2012), Grabowski et al. (2012)	Leonard and Clark (1993), Aronson et al. (1994), Carleton and Done (1995), Vogt et al. (1997), Ninio et al. (2000), Rogers and Miller (2001), Watson et al. (2005, 2010), Houk and Van Woesik (2006), Kenyon et al. (2006), Lam et al. (2006), Leujak and Ormond (2007), Cruz et al. (2008), Tilot et al. (2008), Langlois et al. (2010)

Table 6
Metrics computed from the main video techniques. The list of metrics may depend on the particular implementation of the technique.

Technique	Fish and Macrofauna-related metrics	Benthos- and Habitat-related metrics
RUV and DOV	Frequency of occurrence, presence/absence per species Species richness Abundance or abundance density per species or per size class of the species: maximum abundance seen during the observation period, or mean abundance over viewing intervals during the observation period Number of bites by herbivores Distance from fish to the camcorder Occurrences of activities per individual	Percent cover of abiotic substrate Habitat topography and complexity Percent cover of epifauna and epiflora
BRUV	Number of species within the field of view during the observation period Maximum fish abundance seen during the observation period Maximum number of individuals per species simultaneously observed during the observation (MaxN) Time to first appearance per species	
TOWV	Abundance and percent cover of some macro-invertebrate species	Abundance of epibenthic species Percent cover of epifauna and epiflora Percent cover of biotic and abiotic substrate and habitat Habitat topography and complexity

on taxa (Watson et al., 2010; Pelletier et al., 2011), thereby determining distinct observed assemblage structures (Table 8).

Directly comparing techniques in the field is rather difficult in that observations may be influenced by many factors, either natural or linked to fine-scale system deployment. Paired observations are needed to control for observation conditions, such as time of the day, weather, and the precise observation location. But since implementation in the field may depend on the technique, the number of observations that can be carried out within a given time period, as well as the habitat and depth constraints, may also differ from one technique to another. Thus, a paired comparison may only address the issue of comparing two observations of the same seascape and species, and not the actual advantages and shortcomings of each technique, and therefore not all facets of their complementarity.

For comparisons involving a diver-based technique, i.e. UVC or DOV vs TOWV, RUV or BRUV, the main differences between techniques were due to the presence of divers. The influence of divers' presence on UVC observations has been widely documented (Chapman et al., 1974; Harmelin-Vivien et al., 1985; Kulbicki, 1998; Dearden et al., 2010). UVC also raise a number of additional issues such as the need for species identification skills, the variability of observations between divers, and the influence of swimming speed (Brock, 1982; Bell et al., 1985; Lincoln-Smith, 1988; Kulbicki et al., 2010; Dickens et al., 2011). In the case of diver-free video observations, the factors inherent in each technique, that may affect observations, have not been evaluated from specifically designed studies. These include, for instance, the bait plume or noise, the use of artificial light, and more generally the behaviour of animals with respect to the video system. In addition, the area actually surveyed by each technique inevitably affects the number of species and individuals detected.

Hence, many factors can explain differences between observations obtained from distinct techniques. Because not all these factors can be controlled, it is important to bear them in mind when interpreting the outcomes of comparisons.

From the published studies, no single technique clearly appears to outperform the others; although some are more appropriate for particular purposes. Thus RUV appeared as an appropriate diver-free observation technique, as it can be left in place for a long time, at a range of depths, and in low light conditions when using additional lights (see Supplementary material B, C and D for detailed outcomes of the comparisons in Table 8). It can be used to investigate areas, parameters and factors that cannot be observed from techniques relying on divers, and it enables a high level of temporal and spatial replication. RUV was often found appropriate for surveying common and conspicuous species. BRUV was found particularly appropriate for sampling generalist carnivores, large predators and mobile species. Because it relies on attracting species, it may be usefully deployed in areas when fish are scarce, e.g. pelagic areas or sandy substrates in lagoon areas. The main advantage of TOWV lies in its ability to sample a large area in a short period of time, thereby increasing the spatial coverage of habitats, and the probability of observing species, including rare species (although motile species may be sensitive to boat noise). DOV was deemed adequate for studies at smaller scales, e.g. to study changes in corals, gorgonians and macro-algae, and to provide representative observations of fish abundance and species diversity. The various techniques should thus be seen as providing complementary standpoints on shallow biodiversity and species.

4.2. Cost-efficiency considerations

In addition to the information provided by each kind of observation, investment and operating costs are crucial parameters when considering an observation technique. Overall, few papers documented implementation costs for the techniques used, whereas the time required for image analysis is often seen as a shortcoming of underwater video techniques. Francour et al. (1999) found that underwater video was more cost-efficient than UVC in terms of total time spent in the field and in the laboratory. Based on a subset of papers, Murphy and Jenkins (2010) found that relative costs were AUD$1000–5000 for RUV and AUD$5000–10,000 for BRUV. However, financial costs are difficult to evaluate for a given technique, because of the various ways of manufacturing systems, and because of differences in the characteristics of the camcorders and sensors used. It is thus more relevant to compare required staff time rather than financial costs of equipment. Note also that time spent at sea is always more expensive than laboratory time (Pelletier et al., 2011; Bernard and Götz, 2012). The cost-efficiency of several observation techniques were compared by Leujak and Ormond (2007) (six techniques for surveying coral communities) and by Langlois et al. (2010) (stereo-BRUV versus stereo-DOV transects for observing fish assemblages) (Table 9). Pelletier et al. (2011, 2012) detailed observation costs (including both field and image analysis) for DOV and ROT-RUV, with respect to UVC.

Cost-efficiency considerations must account for the fact that a technique which is better at observing or detecting species, either because of attraction (BRUV) or because of a higher image resolution, will inevitably require increased time for image analysis. For example, Bernard and Götz (2012) found that a BRUV station

Table 7
Studies comparing techniques. NR indicates that No reference was found in the literature search. Only studies with a protocol aimed at comparing data from distinct techniques were quoted.

	RUV	Stereo RUV	BRUV	Stereo BRUV	TOWV	DOV
RUV	NR	Harvey et al. (2002b)	Harvey et al. (2007), Bernard and Götz (2012)	NR	NR	NR
Stereo BRUV	NR	Watson et al. (2005)	NR	NR	NR	NR
TOWV	NR	NR	Morrison and Carbines (2006), Monk et al. (2012)	NR	NR	NR
Stereo	NR	Watson et al. (2005)	NR	Watson et al. (2005), Langlois et al. (2010), Watson et al. (2010)	NR	NR
DOV						
UVC	Francour et al. (1999), Cooke and Schreer (2002), Fox and Bellwood (2008b), Burge et al. (2012), Longo and Floeter (2012), McCauley et al. (2012)	Harvey et al. (2001a,b, 2002a, 2004), Cappo et al. (2003)	Willis and Babcock (2000), Willis et al. (2000), Westera et al. (2003), Langlois et al. (2006), Morrison and Carbines (2006), Stobart et al. (2007), Colton and Swearer (2010), Burge et al. (2012), Lowry et al. (2012)	NR	Morrison and Carbines (2006), Assis et al. (2007), Leujak and Ormond (2007)	Greene and Alevizon (1989), Michalopoulos et al. (1992), Leonard and Clark (1993), Rogers and Miller (2001), Tessier et al. (2005), Lam et al. (2006), Pelletier et al. (2011)
Fishing	Cooke and Schreer (2002), Wells et al. (2008)	NR	Ellis and DeMartini (1995), Willis et al. (2000), Cappo et al. (2004), Morrison and Carbines (2006), Bloomfield et al. (2012)	Harvey et al. (2012c), Langlois et al. (2012a)	Morrison and Carbines (2006)	NR
Acoustic	NR	NR	Gledhill et al. (1996)	NR	NR	NR

Table 8
Main outcomes of comparative studies involving video techniques (see references and Supplementary material B, C and D for details). For each topic of interest, symbols " > ", "≥", " ≠ "," ≈" compare the number of items or the assemblage structure detected by the two techniques, which may represent a qualitative summary over several results.

Outcomes	References
Fish: species richness	
UVC > H-BRUV > V-BRUV	Langlois et al. (2006)
UVC > BRUV	Colton and Swearer (2010)
UVC > RUV	Francour et al. (1999)
RUV > UVC & Experimental fishing	Cooke and Schreer (2002)
UVC ≥ DOV	Pelletier et al. (2011)
UVC > DOV	Greene and Alevizon (1989)
TOWV > UVC	Assis et al. (2007)
BRUV > RUV & DOV	Watson et al. (2005), Bernard and Götz (2012)
RUV > BRUV	Harvey et al. (2007)
BRUV > DOV	Langlois et al. (2010), Watson et al. (2010)
BRUV > Exp. Fishing/Traps	Ellis and DeMartini (1995), Harvey et al. (2012b)
Fish: Assemblage structure	
UVC ≠ BRUV	Colton and Swearer (2010)
BRUV ≈ UVC	Westera et al. (2003)
BRUV ≠ RUV ≠ DOV	Watson et al. (2005)
BRUV ≠ DOV	Langlois et al. (2010), Watson et al. (2010)
BRUV ≠ TRAWL	Cappo et al. (2004)
BRUV > Traps	Harvey et al. (2012b)
Fish: Abundance	
UVC > BRUV	Langlois et al. (2006), Colton and Swearer (2010)
UVC ≥ DOV	Pelletier et al. (2011)
TOWV > UVC	Assis et al. (2007)
RUV > UVC & Exp. Fishing	Cooke and Schreer (2002)
BRUV > RUV	Harvey et al. (2007), Bernard and Götz (2012)
BRUV ≠ DOV (depends on family)	Watson et al. (2010)
UVC ≠ DOV (depends on family)	Pelletier et al. (2011)
BRUV > Traps	Harvey et al. (2012b)
Fish: Occurrences	
BRUV > Experimental fishing	Ellis and DeMartini (1995), Harvey et al. (2012b)
Habitat-benthos	
UVC > DOV: Diversity of coralline algae observed	Leonard and Clark (1993)
DOV ≈ UVC: Live coral cover	Rogers and Miller (2001)
DOV > UVC: % Coral cover	Lam et al. (2006)
DOV < UVC: Occurrence of Gorgonians & Macroalgae, % Bleached coral	Rogers and Miller (2001)
TOWV > UVC: % Benthic cover	Leujak and Ormond (2007)

required 7 h of staff time versus 3.5 h for RUV, but this was mostly due to the fact that BRUV detected more species and individuals than RUV (Table 9). Consequently, a larger time for post-field analysis should not be considered as a weakness if higher diagnostic power is the end result (Bernard and Götz, 2012).

5. Underwater video in the light of current monitoring challenges

As mentioned in the introduction, conservation objectives and sustainable management of coastal biodiversity and resources involve monitoring the status of several biodiversity components in large areas. This is the case for MPA assessment and for regional or global conservation agendas. Present global commitments to reduce biodiversity loss entail setting up MPAs in most regions of the world. MPAs are not only more numerous, but also larger, and how they achieve conservation objectives must be assessed.

Table 9
Cost-related information per technique.

	Reference	Staff time per station (hrs)
RUV	Bernard and Götz, 2012	3.5
	Pelletier et al. (2012) (ROT-RUV)	0.5–1.6
BRUV	Langlois et al. (2010) (stereo-BRUV)	1.75–3
	Bernard and Götz, 2012	7.0
	Gladstone et al. (2012)	1.5 (soaktime only)
DOV	Leujak and Ormond (2007)	
	Langlois et al. (2010) (stereo-DOV)	0.75–1.8
	Pelletier et al. (2011)	0.4–2.5
TOWV	See Table 3	Depends on tow length
UVC	Pelletier et al. (2011) (strip transect)	0.75–1.5
	Bohnsack and Bannerot (1986) (stationary point count)	0.2
	Leujak and Ormond (2007) (Line Intercept Transect)	1.25

Consistently with MPA conservation objectives (Pelletier, 2011), monitoring and assessment should include fish and macroinvertebrate resources, but also fixed fauna, essential habitats, and protected or emblematic species. Maintaining the diversity of taxa and the functioning of species assemblage are additional conservation objectives. Yet, biodiversity is rarely observed and assessed on large spatial scales due to observation costs.

Underwater video may help in making good some of these monitoring gaps. Three main questions are generally raised by the use of video techniques for observing and monitoring biodiversity, species and habitat in shallow waters: (i) how much does it cost?; (ii) is image analysis (i.e. identifying and counting species) an issue?; and (iii) what are the observation area and the required duration of observations? Cost-efficiency questions were addressed in subsection 4.2 when comparing video techniques. Issues (ii) and (iii) are addressed below in subsections 5.1 and 5.2. We will then discuss the two main advantages of most underwater video techniques: their non-obtrusive nature and the potential for high replication (subsections 5.3 and 5.4). Finally, we will compare the advantages and shortcomings of observation techniques in subsection 5.5.

5.1. *Is image analysis an issue?*

The issue of image analysis is often raised by the use of video, in particular the ability to identify and count species, along with the time required to do this. Underwater visibility is a limitation for all visual techniques, whether UVC, video or photo. However, divers conducting UVC or DOV may compensate for reduced visibility by moving toward the observation target. Moreover, the larger the observation surface area, the more critical the visibility. In this respect, RUV may be more dependent upon visibility than BRUV which attracts species closer to the camcorder. High Definition was not always used in recent studies, yet we believe it substantially improves the quality of the resulting data at little extra cost. Being able to take time to identify and count, including the possibility of consulting identification books or experts is actually convenient. Because video footage is archived, it may be shared and analysed independently, thereby enabling discussion about identifications and cross-validation of image analyses. In addition, archiving footage ensures data traceability. Identifying species and counting individuals from two-dimensional images may be initially challenging to people trained in other techniques, but most people learn to do so within a month or two.

The second issue concerns the time needed for image analysis. From our experience, the post-treatment of images balances the time gained in the field through diver-based visual techniques (Pelletier et al., 2011, 2012). This required time may vary depending on the kind of information extracted, e.g. the list of taxa studied, and on the experience of the observer. But it is mostly dependent upon the abundance and species richness in the observation area, which should not be seen as a drawback (see end of section 4).

5.2. *Observation area and duration*

Video techniques exhibit large differences in terms of information provided. First, observed surface areas are not all the same. Horizontal RUV enables observed surfaces and distances to be estimated through horizontal vision, in a similar way to UVC. However, the accuracy and precision of these estimates, whether from RUV or from UVC, should not be neglected. Delineation of the observed surface area (e.g. from strip transects) or mark setting to standardize surveyed areas is possible, but inevitably increases observation duration and may influence observations, because it requires divers. Stereo-video makes it possible to precisely estimate the observation distance and the size of observed individuals, which are otherwise visually estimated either from post-field image analysis (RUV, TOWV, non stereo-BRUV, DOV) or underwater (UVC). For such visual estimations, training from silhouettes has proved useful (Thompson and Mapstone, 1997; N. Guilpart, D. Mallet, D. Pelletier, unpublished data). For vertically-oriented systems (TOWV or RUV), the observed surface may be estimated based on lens and zoom parameters, provided that the camera elevation above the floor is controlled and known. In the particular case of BRUV, the unknown bait plume prevents the evaluation of the actual surface concerned by the observation.

Regarding observation duration, BRUV is constrained by effective bait attraction, which needs a minimum amount of time, from 25 to 40 min (Willis and Babcock, 2000; Watson et al., 2007; Bernard and Götz, 2012). TOWV allows continuous recording of images along the vessel trajectory and footage is often subsampled for image analysis (see references in Table 3). The duration of a single RUV observation varies from a few minutes to an hour (see references in Table 5), depending on the study objective and the system characteristics.

5.3. *Non-obtrusive observations of species assemblages?*

Underwater video techniques provide direct observations of species in their natural habitat, and they are not extractive. Diver-free video techniques are also less intrusive than UVC (see section 1 for references). Among these, TOWV may disturb the ecosystem through vessel noise, though this can be circumvented by using appropriate engines. BRUV data rely on bait attraction within an unknown distance around the observation system. In this respect, observations resemble fishing data, as they are selective, depending on both species and bait. The effect of bait composition and size on catch was well studied (Salia et al., 2002; Smith, 2002; Lowry et al., 2006; Alos et al., 2009; Dorman et al., 2012), as was the behaviour of species near baited fishing gear (e.g. in deep environment: Craig et al., 2005) or near fishery discards (Hill and Wassenberg, 2000). But the distance and range of attraction of vagile fauna by the bait is difficult to test, and to our knowledge, no such study was published at the time of the review. Regarding (unbaited) RUV, our own experience indicates that while some fish already present nearby may be curious when a system is first set up, they rapidly resume their normal behaviour, and the video system does not seem to attract distant fish (D. Mallet and D. Pelletier, unpublished data).

Table 10
Comparison of the main advantages and shortcomings of each observation technique and recommendations for future use. UVC, fishing and acoustics are reported for comparison.

Methods	Advantages	Shortcomings	Recommendations
RUV	Non extractive. Least invasive method. Constant observation duration. Does not require diver. Possible observation at large depth. Fast implementation. Possible participation of non-scientific staff	Duration of image analysis. Management of large data sets	Diurnal and seasonal patterns of behaviour, species activity and abundance over long periods/at high frequencies. Monitoring of conspicuous and target species. Highly spatially-replicated designs
BRUV	Non extractive. Increased observed fish abundance through baiting. Constant observation duration. Does not require diver. Opportunity to work in deep water. Possible participation of non-scientific staff	Unknown effect of bait plume. Relatively long observation duration. Duration of image analysis. Management of large data sets	Monitoring populations of fishes, and particularly carnivorous species. Monitoring in areas where diversity and abundance are low
TOWV	Non extractive. Does not require diver. Opportunity to work in deep water. Fast implementation. Large spatial coverage. Possible participation of non-scientific staff	May disturb the ecosystem due to vessel noise. Management of large data sets. Duration of image analysis	Monitoring habitat and fixed benthic species over large areas
DOV	Non extractive. Does not require scientific diver	All effects associated with the presence of a diver underwater (see below). Duration of image analysis	Study benthic cover and macrofauna
UVC	Non extractive. Widely used. Possible participation of volunteers for simplified protocols	Observer effect. Diver effect. Depth limitation. Requires diver trained to species identification and counting. Observation duration	Studies at species level. Inventories and species counts. Small species
Fishing	Extractive. Does not require diver. Possible observation at large depth. Possible participation of fishers	Unknown observation volume and species catchability	Monitoring of resources
Acoustics	Non extractive. Spatial coverage. Possible observation at large depth	High-tech analysis of data. No species identification	Monitoring of resources coupled with another technique, e.g. fishing. More suitable for pelagic species

5.4. Temporal and spatial replication

With the exception of DOV, for which the number of observations that can be carried out per day is limited by diver's presence (although DOV is quicker than UVC in the field), a large amount of data may be collected per day, making it possible to accomplish highly spatially and temporally replicated designs. Most RUV techniques were indeed designed to be set for a long time and to provide information on behaviour, diurnal rhythms and species activity over long periods of undisturbed observation. This enables an array of questions to be addressed that cannot be studied by other observation techniques. The ability of video systems to produce a large number of observations can also be used in a spatial perspective, for instance to investigate changes in macrofauna and population behaviour, and to correlate communities with environmental variables or anthropogenic pressures. Hence, the response of biodiversity to fishing, MPA protection and other impacts of coastal uses may be addressed at relevant scales. Observation designs may be properly replicated with respect to factors influencing the distribution of biodiversity, such as site and habitat on several scales. A high level of replication then enables relationships between biodiversity metrics and environmental variables to be investigated by increasing the statistical power of analyses and diagnostics.

Beyond the replication issue, the consistency between data collected in distinct areas by different teams is reinforced by the use of identical systems. Within an ecosystem-based approach to fisheries management, a better understanding of the temporal variations in spatial patterns of biodiversity and resources is needed. In this respect, diver-free techniques may at the same time enable small-scale studies with an increased resolution and enlarge the spatial coverage of designs up to the ecosystem scale. For DOV, data consistency is also increased, as there are no differences between videos filmed by distinct divers. Moreover, additional sensors can be coupled to video systems and thus collect additional information on biotic and abiotic variables, as recently advocated by Johnson et al. (2013).

5.5. Which technique for observing and monitoring coastal biodiversity?

The choice of a video technique first depends on the object of the study. Reviewed applications of video techniques in shallow waters were listed in Section 3. These are only a sample of the potential use of each technique, as in this area, technological progress is swift (subsection 2.6) and there is room for innovation and alternative types of implementation. General recommendations may thus be made regarding the scope of each technique (Table 10, last column), but these main features should be seen as indicative rather than prescriptive. For instance, none of the references specifically dealt with the observation of juvenile or larval fish. Yet this could be achieved by several existing RUV techniques, by setting them in appropriate locations with adequate camera settings. Likewise, shy species may be monitored using automated systems regularly recording species activity. Indeed a wide spectrum of applications is feasible with the current technologies.

There are still advantages and shortcomings associated with each technique. These were discussed in the previous subsections (5.1 to 5.4) and summarized in Table 10. Choosing a technique must thus stem from both the general features of each technique and their proven outcomes, but technical adaptations and fast technological changes should also be taken into account. The techniques most often used for observing and monitoring coastal biodiversity and resources remain UVC, fishing and, to a lesser extent, acoustics. This situation prevails for both research studies and management-oriented monitoring. Although not recent, the advent of video techniques has not altered this situation. Indeed, many video systems developed in the past only served during a given research project, and were not intended to be transferred to other contexts or users. This situation changed with the development of BRUV, where the same technique is now repeatedly used in many different contexts.

In the process of selecting a technique for a given study, investment and operating costs are two crucial parameters, particularly when replicated designs involving a large number of observations are envisaged. Although these costs were not often documented in the papers, the review showed that compared to UVC, (i) video techniques generally involved less time spent on the field at the expense of more time spent in post-treatment, for image analysis; and (ii) a lower level of scientific expertise was required during field work. Other features may vary from one technique to another (see Section 2 for description of techniques).

5.6. Future prospects for underwater video monitoring

The technological progress seen in the last decade (see subsection 2.6) will continue, so that system autonomy, storage capacity, and sensor resolution will increase. Human-operated systems will continue to be used, particularly for research and in the context of participative management in coastal areas. But there is a wide scope for automated systems. These can be permanent stations with multiple sensors, either cabled (see e.g. ESONET project: http://www.esonet-noe.org/About-ESONET and Aguzzi et al., 2011, 2012) or mobile systems transmitting information, e.g. programmed gliders (Moline and Schofield, 2009). Such advances will considerably increase the amount of data collected by underwater video systems (among other techniques). It will thus be essential to analyse and manage these large data sets. Automated image analysis will be key for gaining time. Several projects have been set up with this objective, see for instance the Fish4Knowledge project, which aims to analyse undersea fish videos (www.Fish4Knowledge.eu, Phoenix et al., 2013). However, species identification and counting not requiring human intervention still remains a challenge. Properly managed data is the second issue, particularly in view of long-term monitoring. Furthermore, data for biodiversity monitoring and assessment are often collected at the scale of an entire ecosystem, and they are to be shared within collaborative projects. Developing shared protocols and data management utilities for collecting and utilizing the wealth of data that will be made available in the future should be a priority.

Global commitments to conservation also entail research issues at larger scales, particularly regarding spatial patterns of biodiversity and ecosystem approaches to management and conservation (Christensen et al., 1996). Hence, for both research and monitoring purposes, observations with improved spatial coverage and resolution should be carried out in all habitats; they should document exploited and non-exploited species, as well as benthic coverage, including sensitive taxa such as sea grass and coral. These considerable information needs cannot be achieved solely through the techniques used so far, and complementary observation techniques are needed, among which video techniques, either on stand-alone basis or preferably combined with other techniques, are definitely a good candidate.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fishres.2014.01.019.

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