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Reviews in Fisheries Science & Aquaculture
April 2019, Volume 27, Issue 3, Pages 380-391
https://doi.org/10.1080/23308249.2019.1601157
https://archimer.ifremer.fr/doc/00487/59906/

Vessel Avoidance Response: A Complex Tradeoff Between Fish Multisensory Integration and Environmental Variables

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Abstract :

The avoidance reaction by fish in front of an approaching vessel is a major source of bias in direct biomass assessment and ecological studies based on fisheries acoustics data. An experiment was carried out to compare echosounder data obtained using a small speedboat and a research fisheries vessel generating significant higher noise above conventional reduced-noise standard. The results show that there was no significant difference between the individual fish target strength distributions, and the numbers of schools recorded by both boats, these schools having similar areas and perimeters. However, the schools detected by the noisier vessel were significantly deeper, and unexpectedly had a significantly higher energy level. These findings suggest that noise-reduced vessels trigger a different vessel avoidance reaction. The noise-reduction standard is not sufficient to reduce avoidance behavior. It is also to take into consideration the ambient noise, which could impair perception of the platform by the fish, and the probability that the acoustic stimuli could be less important than visual perception under some local conditions. The paper introduces the concept of partial avoidance and presents a conceptual diagram of the strength of the avoidance reaction. Last, it is not recommended, because of noise reasons, that vessels routinely used for pelagic stock assessment surveys be changed. Indeed standardized time series, which could be disrupted when switching to a new vessel, are more important than the hypothetical gain from change to quieter vessels. Obviously, all long-term surveys must change vessels; best practice will be to estimate the vessel effect before any change to avoid disrupting the time series and/or perform vessel intercalibration surveys.

Keywords : Vessel avoidance, fish behavior, fisheries acoustics, small pelagic assessment, fish school, boat noise

1. Introduction

The assessment of many ‘small pelagic’ fish stocks is based on echo integration methods (Simmonds and MacLennan, 2005), but such data are subject to major bias due to fish avoidance behaviour (Fréon and Misund, 1999; Ona *et al*., 2007; De Robertis and Wilson, 2010a; de Robertis and Handegard, 2013; Wheeland and Rose 2015). This phenomenon also occurs during trawling operations, and can introduce bias into fishing samples (Ona and Godo, 1987; Engas *et al*., 2000), as well as into fish stock assessment models based on fisheries data (*e.g*., Beverton and Holt, 1957; Hilborn and Walters, 1992). Underwater noise from research vessels, as it has been defined in the literature (Olsen *et al*., 1983; Engas *et al*., 1995; Misund *et al*., 1996; Vabø *et al*., 2002), is assumed to be the main factor governing such behavioural reaction. The swimming reaction to escape in front of the research vessel is mainly due to the three-dimensional radiated noise-field generated by the vessel (Misund, 1987; Gerlotto and Fréon 1988; Misund and Aglen, 1992). This reaction has been studied by many authors since the initial work of Olsen *et al*., (1983), *e.g*., Fréon *et al*., (1992) Hjellvik *et al*., (2008), Patel and Ona (2009) and Guillard *et al*., (2010). The main factors underlying this reaction are due to the noise transmitted by the vessel, as has been reviewed by Mitson (1995). This author concluded that below a given noise signature (defining a radiated-noise-standard for fisheries vessels by two sound pressure level equations: SPL=135-1.66 log f_{Hz} between 1 Hz and 1 kHz and SPL=130-22 log f_{Hz} between 1 kHz and 100 kHz), avoidance reactions are unlikely to occur and fish schools do not avoid the survey vessel, as it was demonstrated *in situ* by Fernandes *et al*., (2000). However, the reliability of this assumption has been questioned. Ona *et al*., (2007) subsequently showed that the reaction triggered by quieter vessels was greater than that triggered by a conventional vessel, followed by De Robertis *et al*., (2008), who subsequently moderated their results (De Robertis *et al*., 2010b;

De Robertis and Wilson, 2011). These contradictory results showed that the relationship between fish avoidance and noise level cannot be described through a simple correlation.

In this study, the avoidance reaction in front of surveying vessel is reviewed around an *ad hoc* investigation of the effect of the noise spectra generated by two different platforms on pelagic fish, including the effects on individual fish and on fish school characteristics (Reid *et al*., 2000). For such a purpose, a research vessel and a speedboat were conjointly used. The noise spectrum of the speedboat was measured, and a comparative analysis of echosounder data from both platforms in an area of shallow water was carried out, as avoidance reactions are obviously higher there than in deeper areas. A conceptual diagram of the avoidance reaction strength is proposed as a function of the distance from which the vessel signal is perceived by fish school or individual fish.

2. Material and Methods

The data were recorded during one of the 'Pelmed' surveys annually conducted in the 'Golf du Lion' (Fig. 1) to assess small pelagic fish stock, mainly anchovy (*Engraulis encrasicolus*) and sardine (*Sardina pilchardus*), in the French part of the Mediterranean Sea (Brehmer *et al*., 2006a; Sanz *et al*., 2008). A specific experiment was carried out during this survey (Brehmer *et al*., 2003a) in quiet sea, during day and night and under low wind conditions between 29th July and 1st August, 2002. Both boats used have aluminium hulls ; the R/V 'L'Europe' is a catamaran used for national assessment surveys (Table 1) and the 'Chlamys' is a speedboat (S/B) with a shallow draught and a flat hull (Table 1) that make it convenient for shallow water investigations. The gross tonnage and engine power of the R/V L'Europe were significantly higher than those of S/B Chlamys. Both were equipped with split-beam Simrad echosounders: an EK-500 with hull-mounted transducer on the R/V L'Europe, and a portable EY-500 and pole mounted transducer alongside the S/B Chlamys (Brehmer *et al*., 2003b)

(Table 1). The pole mounted at mid-ship distance prevented the formation of air bubble behind the transducer. The EK-500 transducer operated at 38 kHz and was a 6.8° * 6.6° circular at -3 dB; the EY-500 was 70 kHz transducer, with a circular beam shape of 11° * 11° at -3 dB. The split-beam echosounders were set in similar configurations with vertical beaming, range set in automatic positions and the local parameters gave a sound velocity of 1540 m s^{-1}. The transducers were calibrated according to the standard procedure (Foote *et al*., 1987), *in situ* for the echosounder on board the R/V L'Europe, and both in water tank (Ifremer, Brest) and *in situ* for the portable device installed on the S/B Chlamys.

2.1. Vessel and Speedboat radiated noise in situ *measurements*

The radiated noise generated by the R/V 'L'Europe' (diesel engine) has been measured on Brest hydrophone field by the Navy (French Navy, 1994). Since then, no significant change occurred on the ship: same engines, propellers and auxiliaries. Analysis was done in third octave analysis, masking lot of tones that are higher than showed spectra (*e.g*., one tone at 36.5 Hz reaches 159 dB re 1 µPA) given in one hertz bandwidth. Estimation of the noise of S/B Chlamys (gasoline engine) was made during an experiment conducted on 9-10 October 2002 (Sète, France). For the S/B, the process was performed using several passages (minimum depth 5 m, hydrophone immersion at 2.5 m) outside the near field (near field range: from the propeller < 1.7 m [at 10 kHz], from the hull < 7 m [at 100 Hz]). During the experiment, strong East wind was blowing between 20 to 30 knots, generating choppy water surface and thus additional acoustic reflection. The background noise 'BN' was measured (checked all the time) to establish what minimum acoustic level coming from the boat can be measured: the Minimum Detectable Signal 'MDS', equal to measured noise plus transmission loss: MDS = BN + 20 log (R) (Fig. 2A). The boat followed strait line passages East and West with CPA (Closest Point of Approach) equal to 15 m (R). 'White' passes were done to set the optimal configuration of measurements recording, real time controlled by headphone, scope and spectrum analyzer, then recording of one valid passage. The spectra was obtained after post processing (unit dB re 1 µPa in one hertz bandwidth). The S/B Chlamys spectra (Fig. 2A and B) were obtained by spectrum analyzer HP 3562A, for three different bandwidths (in Hz): [0 - 200] Hz, [0 - 2000] and [0 - 20 000] in linear frequency scale, averaging during a few seconds around CPA, from 2 to 6 s, several times, observing stability of obtained spectra, transforming HP spectrum toward a spreadsheet program. The accuracy of the measurements was established by comparison between Navy and Ifremer measurements on other ships and submersibles: results are better than +/- 3 dB for frequency 'f' > 1 kHz, much better that +/- 6 dB for 100 Hz < f < 1 kHz. S/B Chlamys measurements below 100 Hz are not visible because of the background noise (except tones). Tone levels were probably lower, because we kept the highest values in post process.

2.2. Analysis of echosounder data

During the experiment, both boats covered simultaneously the same area (Fig. 1), limited by depths between 10 m and 30 m, distance around 8 knots from the shore. The leader boat position was alternately set by the two boats on successive transects perpendicular to the coastline. The distances covered by both boats were similar, but the volume insonified by the echosounder (vertical beaming), was greater for the S/B Chlamys than for the R/V L'Europe (37% greater at the 10-m depth, thus a difference of 0.72 m in diameter and about 2 m at 30 m depth, due to the beam width difference, at point - 3 dB of the directivity diagram). All acoustics data recorded outside the area delimited by the common transects covered by both boats were excluded from the analysis. The school descriptors (Diner *et al*., 2002) delivered by the scientific echosounders were recorded during daytime excluding the transition period. A total for both boats of 312 acoustic schools were recorded, and spatially positioned. The two surveys were simultaneously conducted to cover the same spatial area, *i.e.*, transect (Fig. 1).

2.2.1. Echo-integration by school

The “echo-integration by school” was performed using the “Movies+” software (Diner *et al.*, 2002) applied similarly for data from both echosounders, taking into account the aft draught of both boats. Such method allows us focusing only on fish schools without taking into account echo-integration of individual fish or dense scattering layers. It is used as a standard during annual assessments of French pelagic fish stock (Sanz *et al.*, 2008). The threshold for the volume scattering strength was set at -55 dB, using a 20 log R time-varied-gain ‘TVG’ function (R being the distance between the target and the transducer) and a pulse length of 0.256 ms. Movies+ provides school specifications based on morphometric and energetic school descriptors. The morphometric descriptors were expressed in meters according to elementary samples (Diner *et al.*, 2002). ‘L’ is the length of school, ‘H’ its height, ‘$P_{min.}$’ its minimum depth *i.e.*, the shallowest extent of the school, ‘$Prof_{bary}$’ its barycentre depth, ‘Peri’ its perimeter and ‘A’ the area of the school (m²). The two main school energetic descriptors were ‘En’, the aggregate backscattering cross-section per school (m^2) (Eq. 1) and ‘S_v’, the volume backscattering strength in (dB) (MacLennan *et al.*, 2002). It is be noted that the S_v is related to the energy (‘En’) and the surface area of the school (‘A’) (Diner *et al.*, 2002):

$$En = \sum_{V} \sigma_{bs} \qquad \text{(Eq. 1)}$$

With σ_{bs} Backscattering cross-section (m²)

$$\sigma_{bs} = \left[r^2 I_{bs}(r) 10^{\alpha r/10} \right] / I_{inc}$$

and r: distance (m); I_{bs}: sound intensity reverberated by a target; I_{inc}: incident sound intensity; α: Acoustic absorption coefficient (dB m^{-1})

$$\alpha = 10\log\left[I(z)/I(z+\Delta z)\right]/\Delta z$$

With z: depth (m).

The criteria used to define the limits of the acoustic school descriptors were : $2.10^{-6} <$ Energy $< 100.10^{6}$, 1 < Height < 500, 1 < Length < 1000, 2 < Area < 500, and $-55 < S_v < 0$ (Brehmer *et al*. 2007). These criteria were adapted to select even small schools (< 10 m²). Indeed, their presence informs about the occurrence of a fish school on the path of the vessel, which could partially escape echosounder beam, *i.e*., the school avoids the vessel by lateral movement, the bulk of the school is not observed inside the single narrow vertical beam of the echosounder. Such avoidance is called partial avoidance.

The very small schools (n = 15) were excluded from the data set (n = 312), which had a corrected area equal to 0 (Diner *et al*., 2002) and thus had invalid corrected S_v values (S_v = 10.log (En/A)). Lastly, a second dataset (n = 123) was established to take only the larger fish schools into account. In this set, all the acoustic schools with an area (corrected by Movies+) greater than 10 m² were kept. Variance tests of the platform effect were performed on the distribution of acoustic school descriptors; the descriptors were transformed into a logarithmic scale (non-normal before distribution). Two series of statistical analysis were carried out in the linear domain : initially on the first dataset (n = 297 acoustic schools), and then on the second one (n = 123), including only the schools with an area greater than 10 m².

2.2.2. Target strength measurements

At night, the same area was covered by the two boats, following parallel trajectories separated by 200 meters distance for security reasons, in order to record scattered fish. Target Strength 'TS' values of individual fish (MacLennan and Fernandes, 2002) were recorded, and a total of 10 447 single echoes were detected by the S/B Chlamys, and 3 463 were detected by R/V

L'Europe. The area was divided in three parts of increasing bottom depth, starting near the shore ([depth interval in meters]: shallow area [< 11], intermediate area [11; 23] and deeper area [23; 35]). The Target Strength 'TS' of individual fish (Ona, 1999) was analyzed using Movies+ software (Diner *et al.*, 2002) for the data delivered by the Simrad EK-500, and using EP500 software for the data delivered by the Simrad EY-500 echosounder (Simrad, 1993). The characteristic discrimination of individual targets for both datasets was done as follows: minimum and maximum returned pulse widths: 0.6 to 1.8 times the duration of the transmitted pulse, maximum gain compensation: 6 dB, and maximum phase deviation: 3 phase steps (Simrad, 1993; Jørgensen and Olsen, 2002). Noise thresholds were set at -60 dB for TS measurement using a 40 log R time-varied-gain ('TVG') function and a pulse length of 0.256 ms. A comparative analysis of TS distributions was performed using the non-parametric Smirnov test.

3. Results

Following the investigations used to compare both platforms noise spectra, taking into account weather condition, the results are presented in two parts : firstly, a comparative analysis of the acoustic school descriptors, and then that of the target strength distributions of individual scattered fish.

3.1. Variations in the noise measurements for the speedboat related to weather conditions

The local ambient noise BN generated an almost blind zone for frequency near 20 and 60 Hz (except tones) in the noise level measurements (Fig. 2A and B). However, at constant speed the SPL spectra varied, particularly above 100 Hz, depending on the position of the speedboat relative to the wind direction; in our case the wind was mainly blowing from the east (Fig. 2A). The SPL values were higher (between 1 dB at 100 Hz to a maximum of 19 dB at 10 kHz) when the boat sailed in an easterly direction, *i.e.*, into the wind than when it sailed westward, except at 100 Hz and 6 knots (Table 2).

3.2. Comparative spectral analysis of in-situ noise from both platforms

The averaged spectra show that the S/B Chlamys is significantly quieter than the RV L'Europe (Fig. 2B). There was a noise peak at around 50 Hz for the S/B Chlamys - East trajectory (Fig. 2A), and two smaller ones at 70 and 80 Hz for the S/B Chlamys - West trajectory. Except for the tones, the overall noise levels generated by the S/B Chlamys can therefore be considered to comply with the radiated noise standard (Mitson, 1995) under normal weather conditions. This was not the case for the R/V L'Europe, which generally radiated more than the recommended radiated noise standard for an acoustics fisheries vessel (Fig. 2B).

3.3. Characteristics of school sounder detections: vertical position, morphology and energy

Among the 312 acoustic schools observed, the 15 excluded from the analysis were detected by the R/V L'Europe, *i.e.*, the very small schools. The first dataset (n = 297) included 138 schools detected by the R/V L'Europe which corresponds to a cumulative aggregation backscattered cross section of 2.30 m^2. For the S/B Chlamys, 159 schools were detected, which corresponds to a cumulative aggregation backscattered cross section of 0.45 m^2. The differential of cumulative aggregation backscattered cross section between the two platforms was 1.85 m^2. This represented a difference of 80% in backscattered cross section, which were not observed by the speedboat, but were picked up by the research vessel. The aggregate backscattering cross-section per school, 'En', and the volume backscattering strength, 'S_v', detected by the R/V L'Europe and the S/B Chlamys, were significantly different ($p < 0.001$), with lower average values being found by the S/B Chlamys (Table 3). The schools detected by the S/B Chlamys also had a significant ($p < 0.001$) greater barycentre depth and their minimum depth (‘$P_{min.}$’) were also significantly greater than that found by the R/V L’Europe (Table 3). However, the school areas showed no significant difference (Table 3), and the same results were also obtained for the school perimeter, which seemed to be unaffected by the platform used (*i.e.*, the RV or the speedboat).

In the second dataset, which included only the bigger schools (n = 123), the number of schools detected by both boat was similar: 60 were detected by the R/V L’Europe, and 63 by the S/B Chlamys ($\Delta = 3$). The ‘En’ and ‘S_v’ per school detected by the R/V L’Europe had the same level of significant differences ($p < 0.001$) (Table 3) as for the whole dataset (n = 297); these values were lower for the S/B Chlamys. In this second dataset, the acoustic school ‘area’ was not significantly different for the two platforms, as it had been in the first dataset. The perimeters of the schools were also similar ($p < 0.001$) for both platforms (Table 3). The barycentre depth and minimum depth of the schools detected by the S/B Chlamys were always significantly greater ($p < 0.001$) (Table 3).

3.4. Target strength distribution of individual fish

During daylight, pelagic fish detected by both platforms were aggregated in fish schools and only a few individual fish were detected, and so no TS data were available. At night, no school was detected: fish were mostly scattered as described in many other aquatic ecosystems (Fréon *et al*., 1996) and thus there were numerous individuals in the water column which made it possible to measure ‘TS’. The results showed that the TS distributions recorded by the two boats were similar (Kolmogorov-Smirnov ‘K-S’ test, $p < 0.05$) (Fig. 3). There was no significant difference (K-S test, $p < 0.05$) between the TS distribution recorded on-board the platforms in the three depth areas sampled, *i.e.*, near the shore [< 11 m] and in the two areas with deeper water ([11 m; 23 m] and [23 m; 35 m]). Moreover, there was no significant difference (K-S test, $p < 0.05$) between the TS distributions from the two platforms.

4. Discussion

This section is divided into two parts: firstly the results of the *in situ* experiment done on the speedboat highlight the effect of ambient noise when considering the avoidance reaction *vs* boat noise spectra; secondly, follows a discussion on how echosounder data can be influenced by the platform used to remotely sense pelagic fish.

Measuring the effect of avoidance due to a given vessel through comparative analysis requires having a clear idea of the background noise transmitted by both boats under the hypothesis that noise is the key stimulus producing avoidance. This is the reason why first of all a series of measurements on vessel noise was performed. Then, vessels were compared and the relative impact of different sound transmissions and vessel noise scrutinized. Once this set of results registered, the comparison between the acoustic survey results can be performed. In our experiment, *i.e.*, comparative analysis of research vessel and speedboat, the survey conditions were comparable (area, sampling, time, protocol, etc.). The major methodological difference was that the R/V L'Europe was operating at 38 kHz while the S/B Chlamys was operating at 70 kHz. Although the difference in frequency has no or few impact on the geometry of the detections, it can have a significant effect on the backscattering of the target, and especially on fish target strength (Horne, 2000). (Mouget *et al*., 2019) following Guillard *et al* (2014) protocol have shown that there is no significant difference between the main hydroacoustic metrics from fish with swim bladder using 38 kHz and other usual frequencies as 70 and 120 kHz. The authors concluded to a similarity of density and biomass estimation measurements between 38 and 70 kHz for fish with a swim bladder.

4.1. Platform noise spectra and ambient noise

The *in situ* measurements of boat spectral noise done with a strong wind blowing from the east allow to carry out a comparison with the West radial measurements obtained with a high level of ambient noise due to stormy conditions (Tkalich and Chan, 2002). East passages were performed with engine speed higher than West passages, producing more noise generated by the propellers, mainly in the high frequency range (above 500 Hz). At 10 kHz, the difference could reach 19 dB at 6 knots (Table 2). Due to the wind strength, the MDS level was sometimes close to the noise emitted by the S/B Chlamys, below 300 Hz (Fig. 2A). At several lower frequencies (< 100 Hz), it was not possible to distinguish the noise from the S/B Chlamys from the ambient noise (Fig. 2B).

The noise radiated by the S/B Chlamys under normal weather conditions can be assumed similar to the noise level measured on the West trajectory, although it may well be overestimated when the boat has a strong following wind (*i.e.*, with the wind astern) as occured during our surveys. In any case, the spectral analysis of the S/B Chlamys revealed that much less noise was radiated than from R/V L'Europe (Fig. 2B). *In situ* measurements obtained for the S/B Chlamys showed that this vessel fits well with the recommended ICES limit for the underwater noise of fishery research vessels (Mitson, 1995), except at 70 and 80 Hz. Ideally, the three-dimensional vessel noise directivity diagram (Misund, 1987; Gerlotto, 1988) should be plotted, but this would require expensive military logistic procedures, seldom used The spectrum signatures contain frequency spikes, namely narrow bands of 6 - 10 dB above the common plateau. These spikes can affect fish behaviour in a different way relative to the wide band part (plateau) of the spectrum. The wide band part of the noise plays a role similar to the ambient noise, which can mask or not the narrow spikes (Hawkins and Chapman 1975; Simmonds and MacLennan, 2005). The sensitivity of small pelagic fish targeted by the echo-integration process (in this case mostly Clupeids and

Engraulids) to noise level is situated between 30 and 500 Hz (Pitcher, 1983); Mann *et al*. (2001) have shown that there is some sensitivity to levels over 4 kHz, even if fish auditable distance is a complex issue as otoliths and swimbladder response in a different way in narrow and wide band parts (Popper and Fay 1973; 2011). At the frequencies perceptible to fish, the ambient noise induced by the environment, *e.g*., rain, wind, waves (Tkalich and Chan, 2002) may sometimes generate more noise than the platform, particularly in shallow water areas, due to bottom and surface sound reverberation.

4.2. Effect of the platform radiated noise on the echosounder data

Our experiments, which were done in the same restricted area, and on the same acoustic schools show that the echo-integration by school according to the echosounder data delivered by the two different platforms led to different results. From the ICES CRR 209 (Mitson, 1995), it would be expected fewer and/or smaller schools to be detected by the noisier platform. Nevertheless, we actually detected similar numbers of fish schools and similar school areas on the echograms of the R/V L'Europe and of the S/B Chlamys, whichever dataset was used. The number of fish schools detected by the S/B Chlamys was actually slightly smaller, but this did not appear to be significant: 4% less for the first dataset (n = 297) or 13% considering the 15 schools excluded from the analysis; and 5% less for the second dataset (n = 123). Nevertheless, the sum of the total energy per school was much lower from the S/B Chlamys echosounder data, indeed the difference from the research vessel data amounted to 80 %. Like the aggregated backscattering cross-section per school, the volume backscattering strength, 'S_v', was also significantly higher for the R/V L'Europe ($\Delta \overline{S_v}$ = -3.83 dB).

School positions in the water column provide information about vertical reactions, which reflect platform avoidance reactions (Fréon and Misund, 1999). The school vertical position descriptors reveal significantly different behaviour depending on the platform concerned. The S/B Chlamys generated more vertical avoidance by the schools (Gerlotto *et al*., 1992; Jørgensen *et al*., 2004), because the school barycentre ($\Delta\,\overline{\text{Prof}_{\text{Bary}}}$ = -0.83 m), and particularly the minimum depth, '$P_{min.}$' ($\Delta\,\overline{P_{\text{Min.}}}$ = -3.78 m), were both deeper than those from the R/V L'Europe. On the large school dataset (> 10 m²; *i.e*., n = 123) the same effects were found. The positions of the acoustic schools detected by the Chlamys indicate a greater downward avoidance reaction (Fréon *et al*., 1993; Jørgensen *et al*., 2004) than was observed by the R/V L'Europe. On the other hand, the acoustic school energy descriptors unexpectedly indicate that the S/B Chlamys data were significantly lower than those from the R/V.

The TS distributions recorded by the two boats confirm that, as expected, the fish adopt schooling behaviour during day-time, and a scattered structure during night-time (Fréon *et al*., 1992; Brehmer *et al*., 2007). The analysis reveals that there is no platform-related difference in the TS distribution of the individual scattered fish recorded during the night. Moreover no difference was found between the shallow area and the deeper regions (Fig. 3). It can be concluded either that the fish display an avoidance reaction in the day-time, when they are aggregated in school structures, or alternately that both platforms trigger the same vertical avoidance reaction regardless of their SPL spectra. Detailed *in situ* target strength studies are called for, like those performed by Gauthier and Rose (2002) using a tow system deployed at various depths combined with a classical, hull-mounted echosounder, to obtain accurate data about the effect of the SPL of the platform on the TS values (*i.e*., the TS delivered by the tow system are supposed to not be directly under the vessel perturbation influence). Some works on fish populations with swimmblader have shown that there is no significant difference in the volume backscattering strength and TS measurements measured *in situ* at 38, 70, 120 and 200 kHz (Guillard *et al*. 2014; Mouget *et al*., 2019). In our study, the TS distributions were also found similar between our 38 and 70 kHz measurements from the two platforms. Thus, it can be expected small difference in volume backscattering strength will occur between the 38 and 70 kHz because the difference in the instrumentation or procedures can introduce some bias (even if *ad hoc* corrections are applied, some artefacts can remain) but cannot explain totally a so high difference (~80%) in the volume backscattering strength, as well as the difference in vertical position neither in the school dimensions.

A small boat (*e.g.*, S/B) that is very close to the standard-noise levels recommended by ICES could nonetheless generate a marked behavioural reaction by the fish schools in shallow water, represented by a major loss of energy compared to that observed by the noisier R/V which does not comply with ICES standard-noise levels. As a perspective, the avoidance reactions should be scrutinized using new generation of echo sounders working in modulation frequencies (Demer *et al.*, 2017) which should provide higher accuracy of fish school descriptors and TS measurements. We also have to note that particularly on-board R/V additional noise can be added to the one from engine and propeller, *e.g.*, from power block, water pump, cold stores compressors, etc. Such additional noise(s) cannot or hardly be controlled during a survey and thus increase variability of SPL spectra and thus fish school avoidance reaction.

4.3. The avoidance reaction: not just a simple noise level threshold

The avoidance displayed by fish schools to an approaching vessel could have two spatial components : the school may simply not be recorded on sounder beam due to a horizontal reaction (*e.g.*, Goncharov, 1989; Handegard *et al.*, 2003; Brehmer *et al*. 2006b) which allowed it to escape from the sampling volume along the vessel path, or they may display a downward reaction, and thus are recorded at a greater depth than previously (*i.e.*, than before the disturbance) (*e.g.*, Gerlotto and Fréon, 1992; Gerlotto *et al.*, 2004; Vabø *et al.*, 2002;). The avoidance reaction could also display both spatial components simultaneously (Vabø *et al.*, 2002). Finally, this reaction could also have two temporal components (Olsen *et al*., 1983; Misund and Coetzee 2000): it could occur at a ‘long range’ distance from the vessel (*i.e*., t_{-1}: further ahead on the vessel path) and/or at a ‘short range’ (*i.e*., t_0: below the vessel hull) (Fig. 4). The school energy loss could be due to:

(i) a downward reaction at a short range (t_0): in this case, the reverberated signals (En and S_v) decrease due to a change in the individual fish tilt angle inside the group exhibiting vertical diving behaviour (Huse and Ona, 1996; Gauthier and Rose, 2002). If the diving behaviour occurs at a long range (t_{-1}), the En, but not the S_v, could increase if the school covers the entire sounder beam;

(ii) a lateral reaction, which at a short range (t_0) would lead to fish school density draining (Vabø *et al*., 2002), producing partial avoidance or at a long range (t_{-1}), would lead to complete or partial avoidance behaviour by fish schools, so that entire schools or parts of them are not detected by the echosounder beam, *i.e*., they actively avoid it.

The avoidance reaction generated by our noisy vessel appears to be a simple downward reaction which may or may not have a minor lateral component at a short range; however at a long range (t_{-1}), the school is able to escape from the vessel path. Note that this could be the case for some of the 15 schools excluded from the analysis; they could correspond to a residual part of school that had partially avoided the vessel. In summary, the avoidance reaction generated by the noisy vessel occurs mainly at a long range (t_{-1}), while that generated by the speedboat occurs mainly at a short range (t_0). Fish schools that had not initially reacted to the speedboat at a long range tended, in average, to remain closer to the surface than those detected by the RV, and so they react strongly by the sudden arrival of the platform above them. As a result, they reacted later but more sharply than the schools that had reacted earlier to the R/V. This is reflected by the greater reduction in their school energy (accentuated by their position nearer the surface, because this meant that less of the school area was sampled by the echosounder beam), due to lateral avoidance behaviour. When the platform is detected by at least one fish in an acoustic school, an alarm signal is transmitted to the other members of the fish school, which displays characteristic collective escape movements (*e.g.*, Vabø and Nøttestad, 1997). The stimulus generated by the boats during the day appears to be strong enough to produce a high school packing density (*i.e.*, a decrease in nearest neighbour distance inside the school, which is characteristic of a school under predator attack (Fréon *et al.*, 1993)), and which makes it impossible to detect individual fish. What triggers fish alarm in front of a noisy, moving platform? At present, the community tend to focus mainly on acoustic stimuli, but visual ones must also be considered. As far as the scientific communities are aware of, there is little information in the literature on this point (Fréon *et al.*, 1993; Brehmer *et al.*, 2003a; De Robertis and Handegard, 2013). The vessel effect includes platform noise (Mitson, 1995), but should also include the visual effect of the platform (*e.g.*, its height, shape and colour) and/or its underwater shadow by day and on moonlitgh nights. Indeed for a 15 cm in length sardine, located in the upper part of the water column (0 to 20 m), the detection of a platform around 60 times longer than itself (the S/B Chlamys) or 200 times (the R/V L'Europe) just above it, will obviously trigger an avoidance reaction. Guthrie and Muntz (1993) report that fish react with a startle response to the movement of any object overhead. Vabø and Nøttestad (1997) as Fréon *et al* (1993) report direct observations of the visual effect of a predator attack on fish schools. *In situ* studies of fish schools reveal strong reactions in pelagic fish schools facing a predator within a short range, such as killer whales produce on herring schools (Nøttestad and Axelsen, 1999), or factice tuna produce on *Harengula sp.* schools (Fréon *et al.*, 1993). Lastly Levenez *et al* (1992) have demonstrated effects of light on nocturnal echosounder data that reveal the influence of visual stimuli. All these studies show that visual stimuli have a significant impact on fish behaviour. Visual stimuli also have to be taken into consideration with regard to the detection of alarm signals by fish; particularly by day and in clear shallow water. Although this seems obvious, it is difficult to demonstrate, because of lack of relevant *in situ* data and the variability of (i) fish behavioural patterns, (ii) the physical environment (temperature, salinity, etc.), (iii) local conditions (turbidity, weather, depth, bottom, etc.), and (iv) the visual acuity of the different fish species (Guthrie and Muntz 1993; Thetmeyer and Kils, 1995), which can lead to misleading interpretations. Finally it is proposed a conceptual diagram of the avoidance reaction strength as a function of the distance from which the vessel signal is perceived by the fish school or the individual fish, distinguishing three avoidance types (Fig. 5).

The ability of teleost fish to perceive the platform, taking into consideration both visual and acoustic alarm signals (pressure wave, particle motion and noise), must be investigated by special experiments taking all three spatial dimensions and time (x, y, z, t) into consideration. Future investigations should try to demonstrate the potential effect of local ambient noise on the avoidance reaction, particularly in noisy environments, *e.g.*, in shallow water under bad weather conditions, or in sectors characterized by heavy marine traffic, given the steady increase of anthropogenic sound in the ocean due to the increasing numbers and size of ships. Lastly the avoidance reaction, as distinguished from the stimulus generated by the noise of the platform, needs to be investigated using an *ad hoc* ‘visual platform detection test’ (*e.g.*, Fréon *et al.*, 1993).

5. Conclusion

The ambient noise during bad weather conditions can sometimes mask or at least attenuate the acoustic perception by small pelagic fish of an approaching vessel. The visual effect of the vessel and/or her under water shadow are also likely to trigger an alarm signal for fish avoidance in shallow water by day-time. Such assumption can be supported by Gerlotto *et al* (2004) reporting a vertical avoidance of the school limited to the part below the vessel. It appears that the platform noise effect may be combined with visual stimuli; this implies that vessel noise reduction could not be the answer to fish school avoidance. Our results converge with Ona *et al*. (2007) ones, who reported that the reaction generated by a noise-reduced vessel can in fact be greater than that triggered by a conventional vessel. It is assumed that fish schools display an avoidance reaction either (i) mainly at a long distance at the approach of a noisy research vessel, resulting in a deeper position of the school within the water column, or (ii) mainly at a short distance at the approach of a smaller and quieter boat, leading to a decrease in school energy due to marked density draining, generated by the school's sudden detection of the boat. Lastly, according to our result and the lack of knowledge on the determinism of the avoidance reaction, a best practice should be keeping as consistent as possible the surveys of pelagic stock assessment and thus the vessel currently used, in order to keep a well standardised time series. Obviously, ultimately all long-term surveys must change vessel. Best practice will be to estimate the vessel effect (*i.e*., the main differences) and attempt to reduce the variability introduced into the time series due to a probable new kind of vessel avoidance pattern.

Acknowledgements

The early stage of this work was part of a P. Brehmer PhD thesis(2000-2004) and then supported by Europole Mer (Research Axis 5 - Complex systems for observation, measures and intervention) 2011, finally achieved within the Preface project of the European Commission's Seventh Framework Program (Grant Agreement 603521) and the AWA project (SRFC / IRD-BMBF, grant agreement 01DG12073E). We would like to thank François Gerlotto (IRD) for the theoretical diagram suggestion and Stratis Georgakarakos (UA) for help full comments, as well as Jean-Louis Bigot (Ifremer, Sète) cruise leader of the Pelmed annual assessment survey, Pierrette Duformentelle (Ifremer, Toulon) for her help during the noise measurement surveys, and Laurent Berger (Ifremer, Brest) for his expertise in echo-integration by shoal using Movie+ software. We also thank anonymous reviewers for helpful comments. Dr Patrick Arzelies (Ifremer, Toulon), we would like to expressed here our deep gratitude for the capacity building he provided and interest in our research.

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Table 1

Main characteristics of the Research Vessel R/V ‘L’Europe’ and the speedboat S/B ‘Chlamys’ used during the field experiments. Both hulls were made of aluminium. $^{(*)}$ Four-stroke engine.

Table 2

The difference in the sound pressure level ‘SPL’ (in dB) between the East and West speedboat trajectories (SPL East - SPL West), measured at constant speed with the wind blowing from the East. The SPL difference reached up to 19 dB at 10 kHz, and was always positive except at 100 Hz and 6 Knots.

Table 3

Analysis of variance (ANOVA), univariate tests of significance for the echosounder shoal descriptors, (n = 297), Sigma-restricted parameterization effective hypothesis decomposition. The same test was also performed on the second dataset (n = 123) including only the bigger shoals (*i.e.*, shoals with an area > 10 m^2 were excluded). In meter ‘$P_{min.}$’ is the minimum school depth, ‘$Prof_{bary.}$‘ the depth of the school barycentre, ‘Peri’ the school perimeter, area the shoal area, ‘En’ the aggregate backscattering cross-section per shoal (m^2), and ‘S_v’ (in dB) the volume backscattering strength (* indicates a significant effect).

Fig. 1. The area studied was in the 'Golf du Lion', situated in the French part of the Mediterranean Sea (43°25'N; 03°33'E). In 2002, an area of shallow water (< 35 m) was simultaneously investigated from two platforms: a conventional fisheries research vessel (red) and a small boat (black), both equipped with a scientific echosounder and following the same radials. The diameter of the circles are proportional to the fish school areas.

Fig. 2. (A) Sound pressure level 'SPL' in dB μPa Hz^{-1} ref. 1 m, from 10 Hz to 10 kHz (logarithmic scale), generated by the speedboat S/B 'Chlamys' at 8 knots, in terms of her bearing relatively to the wind direction (Easterly wind). The spectral analysis makes it possible to compare the minimum detectable signal (MDS) to the sound pressure level generated by the S/B Chlamys during our experiment. (B) The Research Vessel R/V 'L'Europe' produced much more noise than the S/B Chlamys. The ICES recommended fisheries vessel noise level is shown in red.

Fig. 3. Individual fish Target Strength 'TS' (dB) distributions, as percentages (n = 10 447 for the research vessel and n = 3 463 for the speedboat), recorded by night time from the speedboat (white) and from the research vessel (black), inside the study area divided into three depth areas: (A) < 11 m, (B) between 11 m and > 23 m, and (C) between 23 and 35 m. There is no significant difference (p < 0.05) in TS distribution between the platforms or between the three depth areas.

Fig. 4. Sketch showing the main differences in the avoidance behaviour patterns triggered by the noisy research vessel (A and B) and the quieter speedboat (C and D), at the boat approach (t_{-1}) and when the boat is above them (t_0), *i.e.*, inside the echosounder beam.

Fig. 5. Conceptual diagram of the avoidance reaction strength (response) as a function of the distance from which the vessel signal is perceived by the fish school or the individual fish. Curve (A): the signal is perceived at long range (*e.g.*, 1 km), and the reaction increases slowly without ever becoming strong corresponding to a low and slow avoidance reaction. Curve (B): the signal is received at medium distance (*e.g.*, 100 m) and causes a greater avoidance reaction. The last case (curve C) the vessel signal is perceived at very short range (*e.g.*, 10 m) and trigger a strong and sudden avoidance reaction. The scale distance is relative and should be adapted according to the vessel characteristics, the ambient noise, the water turbidity, the school or fish position in the water column and their specific hearing and visual. The stimuli in curve C is acoustic whereas in A and B it could be a combined visual and acoustic stimuli. In the case B the sound pressure perceived by fish explain the difference with case C where only hearing capabilities are involved. Example of signal distance come from the three distinct wave of fish school avoidance as defined by Brehmer (2004).

Figure 1

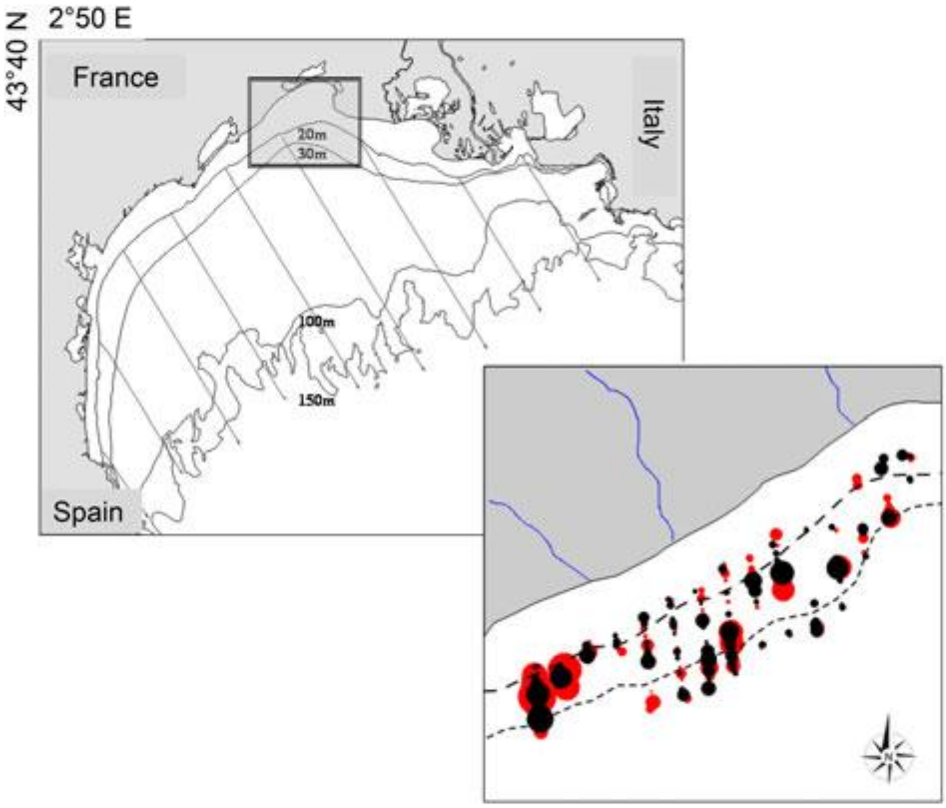
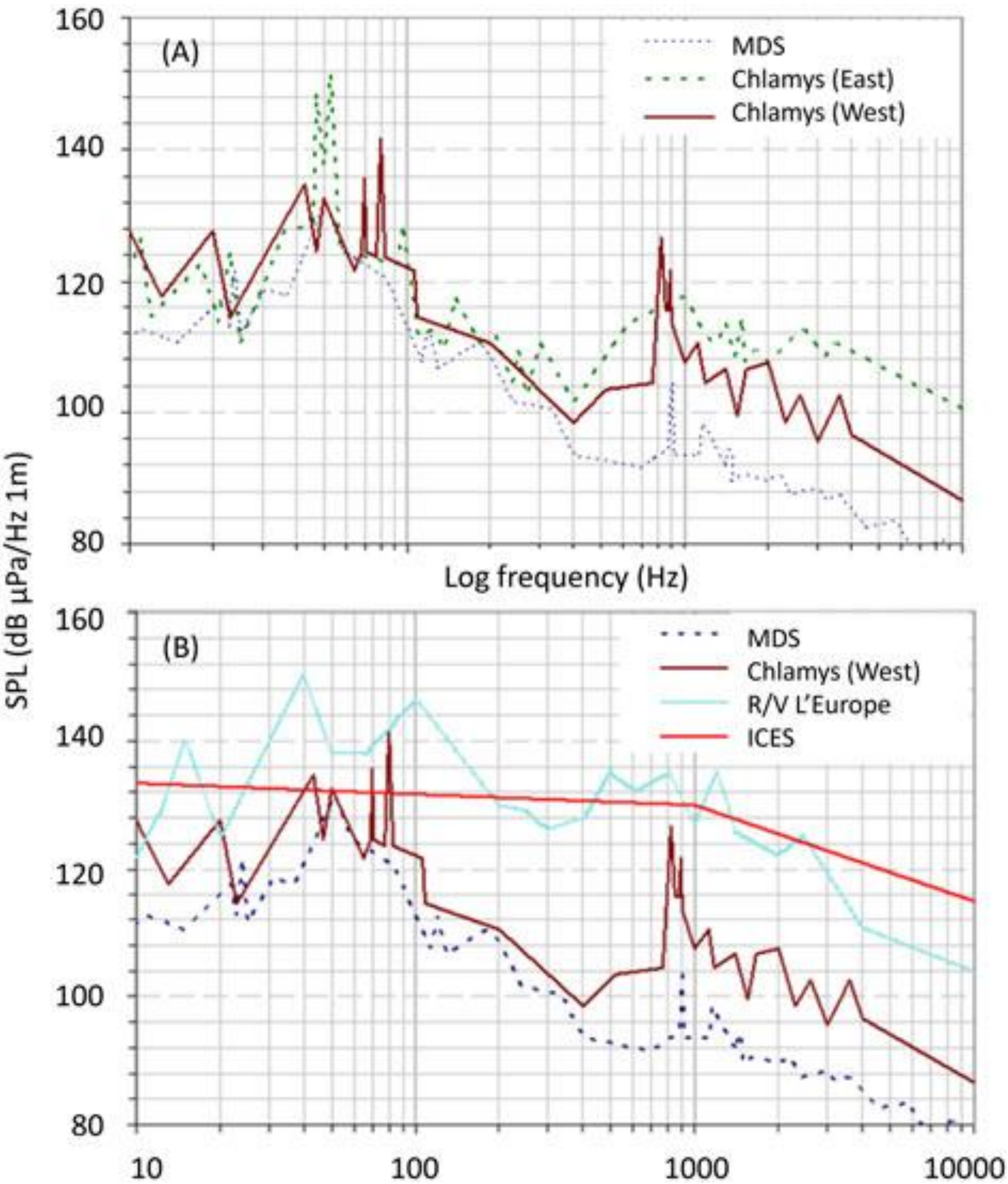


Figure 2



(A)
MDS
Chlamys (East)
Chlamys (West)
160
140
120
100
80
Log frequency (Hz)
SPL (dB µPa/Hz 1m)
(B)
MDS
Chlamys (West)
R/V L'Europe
ICES
160
140
120
100
80
10
100
1000
10000

Figure 3

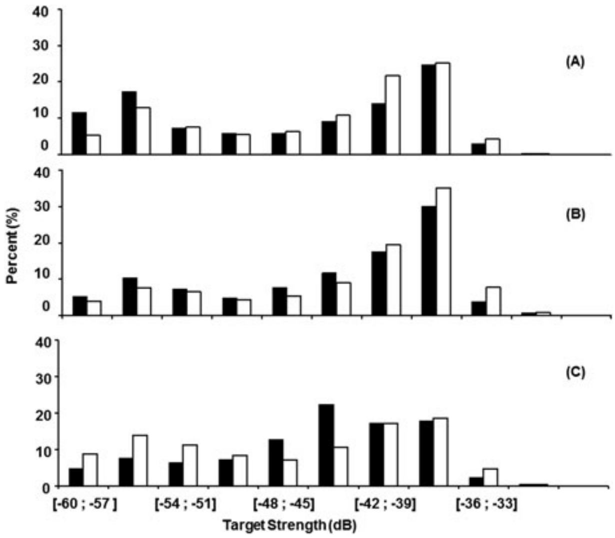


Figure 4

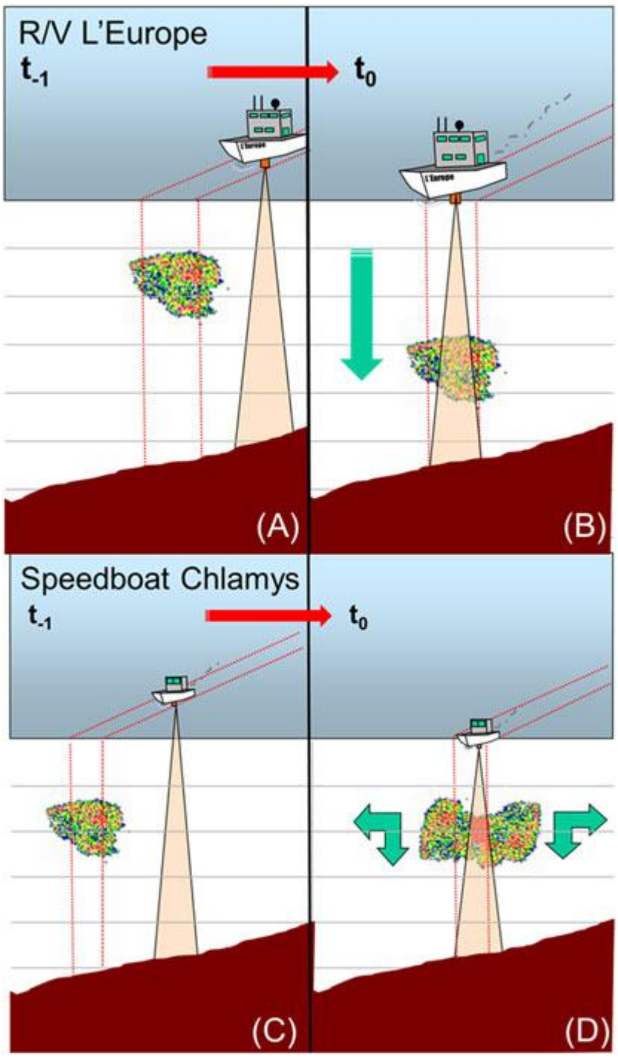
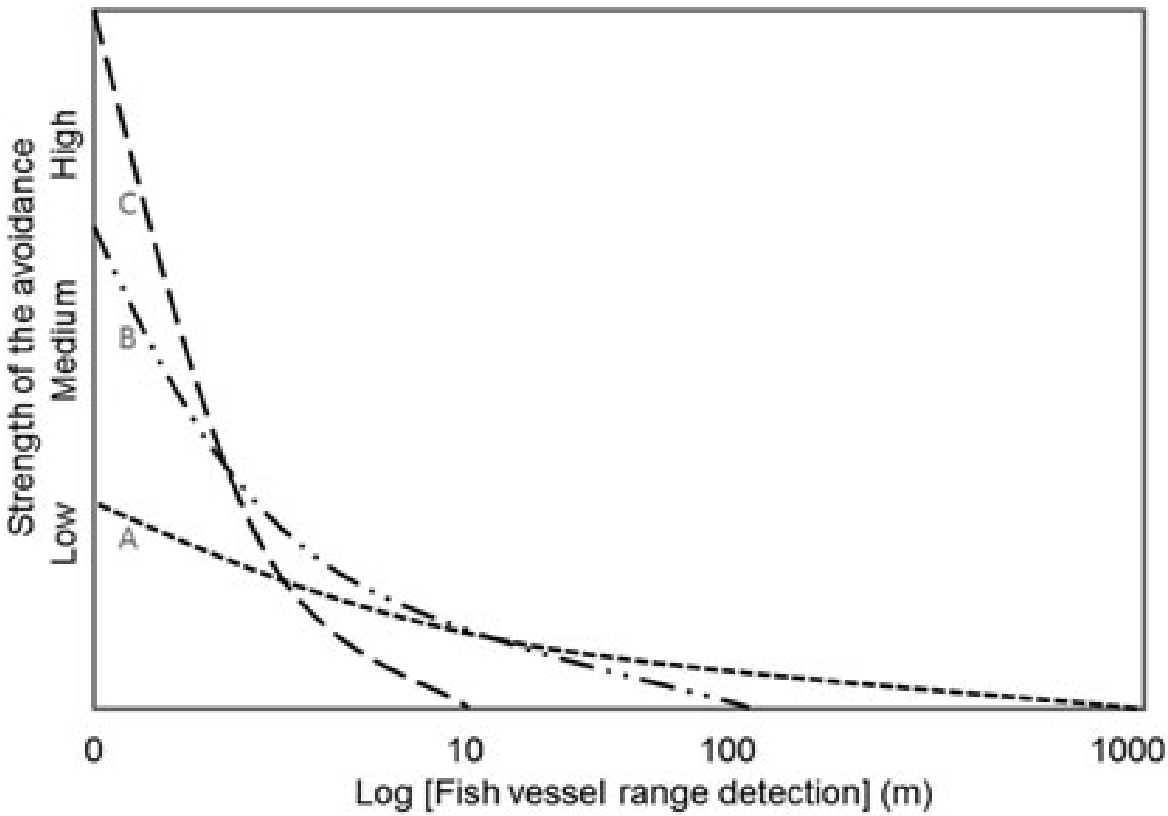


Figure 5



Strength of the avoidance
Low
Medium
High
C
B
A
0
10
100
1000
Log [Fish vessel range detection] (m)

Table 1

Platform specification	RV ‘Europe’	Speed boat Chlamys
Gross t.	264	1.5
Length (m)	29	.6 9
Width (m)	10.	6 3
Aft draught (m)	3.5	0.5
Power (kW)	2_345	2_86
Motor type	Diesel	Gasolinea
Hydraulic block	Yes	No
Generator	Yes	No
Hull color	Blue/White	Blue/Aluminum

Table 2

Frequency Chlamys Speed	100 Hz	1 kHz	10 kHz
SPL East–SPL West (six knots)	–5	3	19
SPL East–SPL West (eight knots)	1	8	14

Table 3

	ANOVA1 (n=297)		ANOVA 2 (n=123)		Average		Minimum		Maximum		Standard deviation	
	F	p	F	p	RV	Chlamys	RV	Chlamys	RV	Chlamys	RV	Chlamys
En	23.69_	0.001	24.82_	0.001	0.0167	0.0028	0.0000	0.0000	0.4956	0.0558	0.0521	0.0077
$P_{min.}$	16.18_	0.001	24.84_	0.001	14.61	18.40	5.00	5.17	27.5	31.59	6.29	5.17
Area	0.29	0.588	3.03	0.083	30.69	20.39	0.50	2.04	394.43	187.94	58.59	30.73
$Prof_{bary.}$	12.29_	0.001	19.12_	0.001	16.21	17.04	5.22	5.00	28.3	30.4	5.82	5.37
Perim	1.28	0.259	0.63	0.428	33.83	37.62	4.76	7.85	133.84	382.54	29.93	43.61
S_v	28.60_	0.001	20.47_	0.001	–40.17	–44.00	–54.7	–54.54	–19.68	–31.75	7.69	5.46

The same test was also performed on the second dataset (n¼123) including only the bigger shoals (i.e., shoals with an area >10m^2 were excluded).In meter ‘$P_{min.}$’ is the minimum school depth, ‘$Prof_{bary.}$‘the depth of the school barycentre, ‘Peri’ the school perimeter, area the shoal area, ‘En’ the aggregate backscattering cross-section per shoal (m^2), and ‘S_v’ (in dB) the volume backscattering strength (_ indicates a significant effect).