ICES SGFARV REPORT

Report from the
Study Group on Fish Avoidance to research Vessels (SGFARV)
Brest, April 2012

Causes and Consequences of Fish Reaction to Fisheries Research Vessels

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Executive Summary
Julia K Parrish, Francois Gerlotto

The ICES Study Group on Fish Avoidance to Research Vessels (SGFARV) was convened in 2007, in response to growing concern that specific recommendations of an earlier ICES Study Group, on Research Vessel Noise (CRR 209, Mitson 1995), and in particular guidelines for acceptable upper thresholds of radiated noise for newly built fishery survey vessels (so called noise-quieted vessels), were not – in and of themselves – enough to insure that surveyed fish would not avoid the vessel. In addition to the basic physiological (that is, detection of a signal) and behavioral (that is, response to a detected signal) issues, a central question concerned whether any detected vessel avoidance by surveyed schools would impact fishery stock assessments as currently practiced.

This report brings together expert authors to consider what is currently known about vessel-based signals that might induce fish avoidance (principally sound), the hearing physiology of fish (principally species of economic import), a behavioral ecology framework within which fish responses to vessels might be considered, a summary and synthesis of experiments to date comparing the responses of fish to noise-quieted versus conventional (that is, existing vessels at the time of publication of CRR 209 and any fishery survey vessels not built to CRR 209 specifications) vessels, and a synopsis of whether and how documented fish avoidance to newly built vessels can impact stock assessment together with instruction on approaches to minimizing that bias.

CRR 209 (Mitson 1995) proposed an upper threshold of noise radiation for frequencies below 1kHz of between 130 and 140 dB re 1µPa @ 1 m (see figure i.1), and suggested that acoustically surveyed fish would not respond to, and specifically avoid, oncoming survey vessels respecting this specification. Since the publication of CRR 209, several field experiments examining fish reaction to noise-quieted vessels have been performed, including: assessment of response to a noise-quieted vessel relative to an autonomous underwater vehicle (Fernandes et al., 200a, b), assessment of response to a noise-quieted versus a conventional (older) vessel as assessed by a
submerged stationary acoustic platform (Ona et al., 2007; Hjellvik et al., 2008; De Robertis et al., 2010; De Robertis and Wilson 2010), and a similar vessel comparison using the vessels themselves (De Robertis et al. 2008; De Robertis unpub. data). Results from these experiments indicate no single pattern, over all experiments, or within systems or species. In some cases, fish appear to respond more strongly to the newer, noise-quieted vessels, whereas in other cases the opposite is true. Within species, differences in response as a function of time of day, time of season, depth, and geographic location are apparent. The strongest effects tend to occur in surface-distributed organisms. In summary, the comparisons of noise-quieted and conventional vessels to date are equivocal.

A central finding, however, is that some fish do respond, and more demonstrably, to noise-quieted vessels. This indicates that, at the very least, these species are detecting a signal. This finding also reveals the fundamental difference between perception of a signal and response to it, and suggests that these are quite different. Thus, while an avoidance response such as diving or lateral movement away from the vessel is absolutely indicative of perception, the reverse (i.e., physiological detection of the signal implies behavioral response) is not true.

Furthermore, these experiments, together with a more comprehensive understanding of the types of signals survey vessels impart, provoke the central question – to which signal(s) are the fish responding? In addition to vessel noise - at low (infrasound), mid (within the hearing range of most fish), and high (ultrasound) frequency ranges – the directionality of vessel noise, it’s tonality, and particle displacement each need to be taken into account. For instance, many of the newer, noise-quieted vessels are significantly larger than their conventional counterparts, calling into question whether increased avoidance reactions, should they occur, are solely due to the intensity of radiated noise. Placing increased emphasis on the links between signal identification and description, physiological detection, and behavioral response is needed before any comprehensive explanation of survey vessel comparison results to date, and likely in future, can be made.

At the center of this issue is whether noise-quieted vessels are able to conduct acoustic surveys of commercially important species with precision at least equal to, if
not better than, older, noisier vessels. Depending on the comparative study (see above) significant differences in abundance estimates as a function of vessel type (noise-quieted versus conventional) were detected (e.g., Box 5.1). Fundamentally, any avoidance of any survey vessel needs to be known, and corrected for, in order to minimize bias in stock assessment. At the same time, the impact of vessel avoidance on stock assessments needs to be judged relative to other sources of bias (e.g., as a function of trawl survey results). Because of the apparent variability of response within and among systems, incorporation of a new survey vessel into an existing time series necessitates multi-vessel (i.e., old versus new) comparisons to allow for the production of robust system and situation-specific correction factors.

Given the variability of the findings to date within the context of the recommendations for vessel design proposed in CRR 209 (Mitson 1995), the Study Group on Fish Avoidance of Research Vessels (SGFARV) concludes that:

- Frequencies above 1kHz, within the range of acoustic survey equipment, are out of the detection range of most fish. Arguments in favor of maintaining this standard therefore come from other quarters than fish reaction, and are not considered here.
- The application of a simple threshold below 1kHz across all species and systems is not sufficient to positively eliminate fish avoidance.
- Investment in noise-quieted vessels may be important for reasons other than minimizing fish avoidance, including but not limited to increasing the signal-to-noise ratio, crew working conditions, and general issues of noise pollution.

**Introduction: Why This Work – Issues Creating the Need**

Francois Gerlotto, Julia K Parrish

In 1992, the *ICES Study Group on Research Vessel Noise* was convened to consider the issue of vessel noise, and the impacts on fish behaviour with specific consequences to abundance estimates as calculated from acoustics. Two problems were considered: (1) the impact of vessel noise on the operation of, and interference with, acoustic equipment; and (2) fish avoidance as a consequence of vessel noise. After a review of the information available at that time, a first approximation was made regarding the acceptable upper threshold of radiated noise below which fish
would not respond (figure i.1) and a Cooperative Research Report (CRR 209: Mitson, 1995, see also ICES, 1995) was published in 1995.

![Figure i.1. Recommendation for a noise-quieted vessel. From CRR209.](image)

The standard presented in this document was then used in the design of subsequent Fishery Research Vessels (FRV), including the Corystes, CEFAS Endeavour, James Cook, and Scotia from the United Kingdom; the Celtic Explorer from Ireland; the G.O. Sars from Norway; and the Oscar Dyson, and Biggalow from the United States.

These noise-quieted vessels largely conformed to the specifications set out by CRR 209, especially at frequencies above 1 kHz. Below 1 kHz, sound signatures varied, with occasional spikes above the recommended threshold. It is also true that the specific sound signature of each vessel differed (figure i.2), despite the design of new vessels being fundamentally quite similar.

![Graph showing sound signatures of different vessels.](image)
Subsequent survey work utilizing the newer noise-quieted vessels suggested that fish avoidance remained an issue, although results of specific comparisons between the effects of older versus newer vessels differed among species and systems, and even within systems between times of year. Whether the avoidance translated into differences in abundance estimation was also variable. The immediate consequence of this work was to throw doubt on the original standard, as the cost of reducing radiated vessel noise, and especially at frequencies below 1 kHz, is substantial.

The original question posed by the members of CRR 209 as how, and how much, does the noise produced by a research vessel affect acoustic abundance estimate as a consequence of fish reaction, including avoidance? The first and simple objective was to evaluate the bias due to fish avoidance, and hopefully to provide a recommendation to reduce it.

Today, we go further and split this original objective into pieces:
• evaluate the survey-specific bias due to fish avoidance;
• determine whether the avoidance is due to noise transmitted by the ship;
• determine what aspect(s) of the noise induce(s) reaction;
• review the values of perception thresholds for fish audition and reactions;
• design inboard methods for measuring avoidance in real time;
• help to improve the design of noise-quieted vessels.

We define three objectives.

Objective: study of the intrinsic characteristics of fish contributing to avoidance. These chapters relate fish physiology (Chapter 3) couched within a behavioural ecology framework (Chapters 6 and 7) to the sound signature of the vessels (Chapter 2).

Objective: measure the actual avoidance reactions to a research vessel. These chapters detail current research on the effects of noise-quieted vessels on fish behaviour (Chapter 4) as well as provide a broader experimental framework for future work (Chapter 7). Experiments on particular characteristics of fish behaviour in controlled media are not sufficient to measure the reactions of fish to a research vessel, for obvious reasons. The only possible way is to work in open field, which brings another set of limitations, and mostly the difficulties of monitoring the environment, and designing a fully controlled experiment. In this case, the three major methods used to date are: observing the reactions of fish from outside the ship (e.g. buoys); comparing results from different vessels (e.g. noise-quieted versus previous generation); or meta-analysis of acoustic surveys within and among vessels, species, and systems.

Objective: consider whether avoidance, if observed, affects abundance estimation. Whether newer vessels are noise-quieted or not, they must be calibrated against existing FRVs in order to insure that abundance estimates do not shift as a consequence of technology rather than population biology. Thus, this objective is a three-step process: (1) determine whether there is a consistent difference in response between existing and noise-quieted vessel, (2) determine whether any observed difference translates into abundance estimation, and (3) determine whether calibration is possible. Chapter 5 examines these questions.
Historically, there has been substantial change in the way fish have been considered in fisheries research. During the period 1950-1990, fish were often represented in a "Cartesian" manner, i.e. as "living machines" with no cognitive capacities allowing adaptive decisions. The origin of this paradigm comes probably from the source of data available, which were almost exclusively from catches (through fishing or research vessels). In most of the models drawn for studying dynamics of populations, no particular individual capacity of initiative was given to fish, and in all these cases the parameters input in the models were those from the fishery, with a few additional variables from the physical environment (wind, currents). This approach influenced research on fish reactions; for instance the avoidance model designed by Olsen et al (1983a), where the reaction of fish was assumed as directly proportional to the intensity of sound. (figure i.3)

![Figure i.3. avoidance model related to radiated noise from a vessel, from Olsen et al., 1983a](image)

Olsen et al., (1983b) specify that "the fundamental problem is that if the behaviour of the fish cannot be observed continuously and accurately, a considerable amount of a priori information seems needed in order to obtain a sufficient level of accuracy of abundance estimation methods (...) One great problem in the proposed model is the necessary "generalization" of behaviour in order to obtain what is regarded as "typical" pattern of behaviour of fish species in a particular biological situation".
There was no other way to work at this period, as behavioural data could not be easily extracted from schools in situ, until the development of digital echo sounders and related software allowing detailed data processing as to school size, shape, density, location, and movement, all as a function of extrinsic factors, including both environmental context and vessel-produced stimuli. Within this framework, the CRR 209 curve (figure i.1) represented a fundamental integration of fish biology and fishery engineering, as it provided a guideline for building research ships with a reference linked to the audition spectrum of fish.

Despite these early estimations, fish avoidance has now been documented at noise levels below this threshold (Chapters 4 and 7). In fact, this result was not unexpected. The authors of CRR 209 stressed that "other factors, both physical and physiological, play a part in determining the noise level that will trigger the avoidance response from fish". The drawback is that, as often, this preliminary remark disappeared from the understanding of users. What remained was a strictly deterministic model where noise intensity and direction were the only forcing parameters. In this field, as more generally in many fields of scientific research, the indispensable simplifying hypotheses became truth.

An important point if we want to address the question of fish reaction is to consider school response to vessels within the context of behavioural hypotheses. Many works presented in the field of fish reactions did not make this effort, and thus it became quite often impossible to draw any synthetic hypothesis, not to speak of general conclusion. It is likely that fish respond to “scaring stimuli” in the same manner they respond to predators. This conceptual framework is explored in Chapters 6 and 7.

To address these new questions, a second ICES Study Group on Fish Avoidance to Research Vessels (SGFARV) was convened in 2007, to synthesize the growing body of experimental work since the publication of CRR 209. The original terms of reference are as follows:

| Term of Reference a-i) |
Many ICES nations have or are procuring quiet fisheries research vessels, at great additional costs relative to conventional vessels. To study the benefits of these new vessels, it is first necessary to understand the physical stimuli produced by vessels that could elicit avoidance reactions.

**Term of Reference a-ii)**

Several countries are conducting or have recently completed significant studies in this area and the subject would benefit from a review of progress and an evaluation of the results obtained.

**Term of Reference a-iii)**

Monitoring of physical stimuli produced by vessel is necessary to determine when and why some fish avoid some survey vessels.

**Term of Reference a-iv)**

Characterizing fish avoidance behaviour is challenging and a review of effective methods will aid researchers.

**Term of Reference a-v)**

New methods and experiments will be needed to better characterize fish avoidance reactions to survey vessels.

**Term of Reference a-vi)**

The SG should disseminate findings via an ICES CRR.

This report details the findings of SGFARV, and includes a reassessment of the issue of fish avoidance and vessel noise. In particular, this report provides:

- a brief history of CRR 209 (Chapter 1);
- a comprehensive assessment of radiated vessel noise and other potential vessel-produced stimuli (Chapter 2);
- an overview of fish hearing with an emphasis on the physiology of sound signal detection by fish (Chapter 3);
- a comprehensive assessment of the experimental work on the behavioural responses of fish and other commercially important species to noise-quieted vessels relative to older, noisier vessels (Chapter 4);
• a determination of the degree to which behavioural responses translate into differences in abundance estimates and a discussion of potential sources of error (Chapter 5);

• a behavioural framework within which to place our understanding of the mechanisms involved in the avoidance process, with specific reference to avoidance to predators (Chapter 6)

• an overview of experimental approaches and considerations needed to create a behaviourally-based threshold of sound signature (Chapter 7);

• and a set of specific conclusions with regard to the standard originally set out in CRR 209 and recommendations for moving forward, given the reality of currently existing survey vessels (old and new) and the continuing need for accurate survey data and assessments (Chapter 8).

We stress that this report, coming as it does so quickly on the heels of new experimental work comparing fish reactions to older generation versus noise-quieted vessels, is only able to summarize a small, but growing, body of work. As such, it is too early to make a conclusive determination as to the efficacy of maintaining, or rejecting, the standards set out in CRR 209. Rather, we provide the most comprehensive meta-analysis to date (Chapter 4), and attempt to place those results within a larger context that is directly relevant to the behaviour of the fish (Chapters 6 and 7), as well as of the physiology of the fish (Chapter 3). A general drawing comparing the scopes of this work with SRR 209 is given in figure i4.

Finally, this report, dealing as it does with fish avoidance and the potential consequences of differential avoidance to population assessments, does not explicitly address the current standard set out in CRR 209 for high frequency (> 1kHz) performance.
Chapter 1. Brief History of the Problem
Dick Wood, Ron Mitson

1.1 A History of Underwater Radiated Noise Related to Fisheries

There is a long history of concern over how the noise radiated by vessels affects fish. This appears to have been first recorded by Shishkova (1958) at a time when diesel propulsion was replacing steam for most vessels. It was nearly ten years later when the Directorate of Fisheries in Norway appointed a Working Group to consider the “need for a systematic investigation of noise conditions of fisheries vessels and possibly suggest a plan for such an investigation.” The subject was, “Noise Problems in Fisheries” and the report was issued from the Vessel-Noise Committee in 1969 (anon., 1969). The background to this was that several interests had pointed out:

- Noise may scare fish
- Noise can make it difficult to find fish
- Noise can be uncomfortable for the crew
A list of items considered to cause noise was produced, but with the comment, “There is not sufficient quantitative knowledge about how these items influence the noise level.” And furthermore that “Many avoidance reaction reports are from the herring fisheries but it is not known which frequencies and levels cause the reactions.” The opinion was that changes in noise level caused by RPM and change of propeller pitch were the stimulus, but that fish adjusted relatively quickly to high but constant levels. The report also made it clear that vessel noise was impeding acoustic assessment: “Noise from the vessel makes it very difficult to use echo sounders and sonar effectively to detect weak echoes and it is hard to predict performance of these instruments because of lack of measurements of vessel noise.”

The conclusions were:

- Several interest groups want noise problems on fisheries vessels further elucidated, aiming at means for noise reduction and to establish simple measurement methods for routine control of vessel noise levels.
- An investigation with a practical aim should be initiated as soon as possible
- The work should be financed by the government

The report then goes into technical detail about noise characteristics of vessels used in fisheries and concludes with a plan of action to be executed by a research institute.

There is no record of a direct follow-up from this in Norway, but in the UK measurements were made on a fishing vessel (Chapman and Hawkins 1967). In 1968, Simrad conducted measurements on the Peruvian research vessel *SNP1* and three other publications on this subject were also seen that year. One was from an ICES CM by G. Hering (1964) and the other was by Y. Maniwa (1968; 1970).

In 1969, two papers on vessel noise and fish avoidance were published by Freytag and Karger (1969), and Traung (1969). At the end of this year, the United Nations Food and Agricultural Organization (FAO) Department of Fisheries organized a meeting and a report of this was published in April 1970. The important conclusions were:

- Ship noise is a significant factor that should be seriously considered at the vessel design stage.
- Compilation of a comprehensive bibliography would be very useful.
• FAO should sponsor reproduction of a standard text on underwater noise as a problem in fisheries – to be used as a general introduction to the subject.
• The meeting report should be distributed to all working on problems in this field and their future collaboration invited, including manufacturers of propellers and acoustic instruments.

FAO then appointed W. Ojak to an André Meyer Fellowship to carry out a comprehensive program of measurements of structure-borne vibrations and radiated noise on the G.O. Sars. In this year, Elminowicz also published the “Echo sounder and sonar self-noise measurements of the vessel Professor Siedlecki.” At about this time, Simrad put together the underwater measurements they had made on 15 vessels, five research vessels and 10 fishing vessels (1969). In 1971, Gjestland reported on noise measurements at the 9th meeting of the ICES Fishing Technology Working Group. In addition to the emerging concerns about avoidance behaviour by fish, this paper reported that due to the improved power and sensitivity of echo sounders and sonars, performance was being limited by vessel noise. In the same year Kjell Olsen (1971) published his paper “Influence of vessel noise on the behaviour of herring.” Physiological and psychological effects of vibration on crews were also addressed. In 1962, I.P. Vatz and R.F. Williams wrote the “Development of noise control specifications for the Woods Hole Oceanographic Research Vessel,” a classic reference Vatz and Williams, 1962).

In 1975, the report of the ICES Working Group Research on Sound and Vibration in Relation to Fish Capture concluded that the problems of vessel noise causing fish avoidance were not diminishing and were also not receiving much attention. In 1976, Shibata published work on vessel noise (1976) and K. Olsen (1976) wrote on the avoidance reaction of fish.

At the same time, some effort was directed towards designing vessels with lower levels of noise signature including the Bjarni Saemundsen and Cirolana (see figures 1.3, 1.4, and 1.5), two direct current (DC) diesel-electric propulsion vessels coming into service in 1970. Despite improvements in mounting machinery and isolating it from the hull, noise levels at low frequencies were not significantly reduced.
A growing body of work in the 1980s included Ona and Cruickshank (1986) “Haddock avoidance reactions during trawling” Bercy and Bordeau (1987) “Effects of underwater noise radiated by tuna fishing boats on fish behaviour” Ona and Godø (1990) “Fish reactions to trawling noise: the signification for trawl sampling” and Boklach (1989) “The effect of fishing vessel acoustic fields on the behaviour of speedy fish concentrations.” Several studies provided increasing evidence that fish can exhibit avoidance responses (e.g. Olsen et al., 1983b; Dimer and Massé, 1987; Ona and Godø, 1990). And furthermore that reaction can occur at separation distances between the fish and the vessel that are on the order of several hundred meters, which suggests that the stimulus propagates well in front of the vessel.

Finally, in 1992, ICES C. Resolution 1992/2:12 gave the terms of reference to the Study Group on Research Vessel Noise. These were: “To specify and summarise available information on the essential requirements for research vessels with a view to recommending measuring procedures.”

Questions posed to the group at its first meeting were related to fish reaction to underwater radiated noise

- what is the stimulus that scares fish in the path of a vessel?
- should we take account of the hearing thresholds and bandwidth for sample species?
- are there enough data available?
- are there programs in place for fish behaviour/noise studies?

The premise of the Study Group work was that the presence of a vessel can impact the behaviour of fish, which may in turn influence acoustic or trawl-based abundance estimates of fish stocks.

Reactions to approaching vessels are of general concern as they have been documented in both freshwater and marine environments for a range of platforms including large ships (Olsen, 1990; Ona et al., 2007), small boats (Xie et al., 2008), and underwater vehicles (Patel et al., 2004; Stoner, 2008). Reactions that influence acoustic measurements of fish abundance are considered to be of particular interest, as
they may introduce bias in assessments of commercially important stocks (Løland et al., 2007; Hjellvik et al., 2008).

Fish are known to respond to visual stimuli from vessels such as deck lights (e.g. Lévénez et al., 1990); however, visual stimuli are unlikely to be the cause of reactions at long range, particularly during the day. The most likely stimulus causing a reaction at long distances was thought to be underwater radiated noise, as vessels were known to produce high levels of radiated noise in the frequency range overt which the hearing of most fish species is most sensitive, and which can propagate over long distances from the vessel (Engås et al., 1995; Mitson 1995). As a result of mounting concern about the influence of vessel-induced reactions of fish on abundance surveys, low-frequency sound (1-1000 Hz) limits for research vessel underwater radiated noise were recommended to minimize vessel avoidance by by surveyed fish (CRR 209).

1.2 ICES CRR 209 Recommendation for Vessel Underwater Noise Control
CRR 209 contained a graph based on fish hearing responses in terms of pressure sensitivity, in comparison to vessel radiated noise levels with the recommendation that vessel-radiated noise characteristics should lay below this.
Figure 1.1: Indicates the aim of ensuring that vessel radiated noise would not cause avoidance behaviour from cod or herring at distances beyond 20 m from the vessel and the method from which it was derived.

A separation of 20 m between vessel and fish was taken as a realistic and practical distance beyond which no fish reaction should arise. The level of "allowable" noise was determined from the literature on hearing studies on cod and herring, by taking the threshold of hearing for these fish as 76 dB then, and assuming a reaction level of 30 dB greater. Assuming spherical spreading, 26 dB was then added to allow for the 20 m distance, yielding a figure of 132 dB re 1 µPa @ 1m. This was then related to the “typical” peak frequency of fish hearing, which was assumed to be at ~ 100/200 Hz for cod and herring. The limit applied at a distance of ~ 20m (i.e., solid red line in figure 1.1). Alternative pressure limits at different distances and for noisier vessels are also set forward in Figure 1.1. However, these sound pressure levels do not address the variation of pressure with frequency. The actual limits set forward in ICES CRR 209 are given by the two expressions that cover frequencies below and above 1 kHz. The lower frequency range related to the fish hearing part of the spectrum, with the higher frequency limits governed by acceptable limits for sonar systems. The levels proposed were:

- 1 Hz to 1 kHz: \( NL = 135 - 1.66 \log f \) Hz
- 1 kHz to 100 kHz: \( NL = 130 - 22 \log f \) kHz
These levels are shown graphically in Figure 1.2 (figure 22 from ICES CRR 209). Although noise-reduced vessels conforming to these recommendations are substantially quieter than their conventionally designed (i.e. not noise-reduced) counterparts over a broad frequency range (Mitson and Knudsen, 2003), the efficacy of noise quieting measures on reducing fish reactions remains less well understood.

1.3 Summary
• Studies provided increasing evidence that fish can exhibit responses consistent with avoidance of vessels.
• Avoidance may cause biased results in abundance estimates, with the potential to impair management decisions.
• A series of workshops considered vessel noise in relation to hearing threshold and bandwidth for targeted species.
• CRR 209 produced a graph of fish hearing thresholds based on fish audiograms, and recommended that vessel-radiated noise for newly manufactured fisheries research vessels (FRV’s) should fall below these criteria.

Chapter 2. The Platform and Possible Stimuli
Dick Wood

2.1 Introduction
The research vessel as a platform does not present great differences from other ships, except that the achievement of acoustic surveys may require two additional conditions:
• the sources of noise stimuli be identified and quantitatively measured,
• to the degree they interfere with scientific activities, these stimuli be minimized.

Otherwise, the background noise (for any stimulus), and above all its possible and unknown variability, affects directly the measurements on all the parameters and
variables that could be studied. This chapter considers sound stimuli from both vessels and the surrounding environment.

### 2.2 Ambient Underwater Noise

Knudsen et al. (1948) published a report that surveyed and compiled the “principle available data on underwater ambient noise” condensed from a much longer survey report. In scope, it covers sources and levels of noise under a variety of conditions and in widely separated localities. Methods of noise generation are well described by Ross (1976). Wenz (1962) and Urick (1986) deal with levels of ambient noise. Short reviews of both the mechanics of noise generation and resulting ambient noise levels are found in McCartney (1971) and Urick (1983).

![Figure 2.1. Ambient and localised noise sources in the ocean. From Coates, 2002 ((c) Seiche ITD 2004, see www.seiche.com) x axis: frequency in dB; y axis: Spectrum noise level [dB re 1 µPa per Hz]]
Noise forming the natural background in the sea can mask the hearing of sensitive fish such that their detection of sound will ultimately be limited by the level of the ambient noise (see Chapter 3 for a discussion of masking of sound detection by noise). Ambient noise is quite variable and can arise from a number of sources (figure 2.1) generally classified as either:

- Physical - wind driven, turbulence, thermal, rainfall, seabed generated, seismic, and icebergs;
- Biological - animal sounds and movement;
- Man-made - shipboard machinery, propeller, water flow around, and discharges from, the hull.

Sound generation is dominated by different physical phenomena in different frequency bands. Above 20 kHz, thermal noise (Mellen, 1952) is generated by molecular collisions. For frequencies between 200 Hz and 50 kHz the main controlling factor is the complex interaction of wind and sea surface. Surface ocean wave interaction (Hughes, 1976) and breaking waves with spray (Wilson, 1980; Kerman, 1984), have been identified as important sources of noise. Wind induced bubble oscillations and cavitation (Furduev, 1966; Ross, 1976) are also near-surface noise sources.

High levels of man-made background noise in relatively local areas can occur when there is an aggregation of fishing or other vessels. It is therefore important to recognise the sources of such noise, its variability in terms of frequency spectrum, level, locality and directionality.

Ambient sound levels are not only the result of noise sources; they also depend on propagation conditions and the absorption of sound in seawater (Francois and Garrison, 1982). Propagation is dominated by thermal conditions in the water, particularly the depth of the thermocline, but the structures of the seabed and sea surface also contribute substantially. For instance, sound is transmitted easily into soft sediments, where it is largely absorbed, but is reflected from rock with much lower losses. Noise levels are reduced by absorption in both seawater and the seabed. Low frequencies propagate for great distances with little absorption in seawater but
the amplitude of high frequency components of noise is diminished with distance. The resulting spectrum depends on the contributions of these different mechanisms of sound generation and conditions of local absorption. Although hemispherical attenuation generally arises upon moving away from a source there are cases, particularly at low frequency, where the sound transmission can be contained within a layer of the sea more representing an acoustic waveguide.

2.3 Description of the Pressure and Spectral Content of Vessel Noise

The frequency and amplitude diversity of the noise shown in Figure 2.2 reflects variation between vessels in vibrations due to a variety of installed machinery. These vessels were built to specifications similar to commercial fishing vessels in terms of the machinery used and general construction and all of them exhibit high levels relative to the threshold levels suggested in CRR 209.

![Figure 2.2: Frequencies and pressure levels radiated underwater by a number of conventional research vessels at speeds of 9 to 10 knots.](image)

2.3.1 Low Frequency (infrasound)

The definition of low frequencies adopted in this report is a wave phenomenon having the general characteristics of sound waves except that its frequency range is below that of sound audible to humans. Generally taken as below 20 Hz, infrasound has been the subject of several fish hearing studies (Sand and Karlsen, 1986; Knudsen et
al. 1992; 1994; 1997; Sand et al., 2002; 2001; see Chapter 3 for details). Most recently, Sand et al. (2008) have pointed out that some fish taxa appear to employ directional avoidance responses to infrasound, and have suggested that large, moving vessels may generate extensive particle motion fields mainly in the infrasound range. As frequency decreases, infrasound ambient noise levels in the sea rise quickly; at around 25 dB/decade between 10 Hz and 0.1 Hz, Nichols (1981).

![Main vibration excitation frequencies](image)

Figure 2.3: Frequencies of vibration from major components installed in a particular vessel. The excitation frequencies in this figure relate to the vessel whose radiated noise levels are shown in Figure 2.9 The propeller has 5 blades and at 11 knots it rotates at 155 RPM.

It is clear from figure 2.3 that vessels produce noise at infrasound frequencies resulting from propeller shaft/engine vibrations. As shown, these arise from the propeller shaft rate, the propeller blade rate and the cylinder firing rate. Of these, the propeller blade rate is usually the most important, with a significant level of tonal content being generated at a frequency of:

\[
\text{(shaft RPM x number of propeller blades)/60} = x \text{ Hz and its harmonics}
\]

An example from Figure 2.2 shows that when running at maximum RPM the blade rate is 13.4 Hz \((\lambda = 112 \text{ m})\) so the second harmonic would be 26.8 Hz \((\lambda = 55 \text{ m})\). But at the maximum RPM the propeller shaft rate is 2.58 Hz \((\lambda = 580 \text{ m})\).
Many vessels are fitted with propellers having controllable pitch (CPP) blades for vessel speed control and a change of a few degrees in blade pitch can result in very large increases in low frequency noise, as shown by Gjestland (1971) and also from “Tridens” data by de Haan (1992). There is also a corresponding change in high frequency noise. A CPP is normally driven by a gearbox which in itself can be the source of high level tones (de Haan, 1992). In a diesel mechanical system, the output shaft of the main engine is connected to a gearbox then goes via an intermediate shaft from the gearbox to a thrust block which is in turn coupled to the propeller shaft. Another type of propeller is variable pitch (VPP), in which the blade angle can be changed by a small amount (but not whilst underway). Measurements of low frequencies (below 10 Hz) radiated from vessels are restricted mainly for the practical reasons given in Section 2.3.

2.3.2 Mid-Frequency (fish hearing)
Following from the definition of low frequency given above, the mid-frequency band of noise extends from about 20 Hz to greater than 1 kHz. This is roughly the range of known fish hearing although most fish are sensitive to a narrower band of frequencies.

A wide range of machinery installed in a vessel is likely to contribute to the noise in this frequency range. With a diesel-electric drive system, the most important machinery sources are generally the diesel engines and the DC propulsion motors. However, with a diesel-mechanical drive system, the most important sources are likely to be the diesels and the gearboxes. But there are numerous additional items of equipment that can influence underwater radiated noise levels including various pumps, compressors, fans etc. Probably the most important single source is the diesel engine which can generate very high levels of hull radiated noise up to 1 kHz and beyond unless rafted, although gearboxes can also radiate very strong underwater noise tones at the gear meshing frequencies (typically 100 – 250 Hz). It should also be noted that cavitation from the propeller is broad band and is therefore a major source of mid-frequency noise for many fishing vessels. Energy in the mid-frequency band, with wavelengths from 75 m to 1.5 m, propagates quite freely with mainly spherical spreading to account for propagation losses but with absorption loss increasing as frequency increases.
2.3.3 High Frequency Emissions (*ultrasound*)

A normal definition of ultrasound is that it occurs above the range of human hearing. Production of high frequency radiated noise is mostly due to the propeller. It arises from the phenomenon of cavitation which causes small bubbles to form then collapse rapidly thus giving rise to wideband noise. The most common form of cavitation originates from the tips of propeller blades but several other sources can exist (figure 2.4). Cavitation can also occur where there are projections from the hull (such as any bilge keels) or cavities within the hull (such as unprotected thruster tunnels). Cavitation can also be generated due to the presence of rough surfaces, particularly when these lie outside the boundary layer of the vessel.

Above about 10 kHz, propagation is increasingly restricted to some extent by the factors of water temperature and salinity that are related to absorption losses. Depth also plays a part but for the purpose of this report need not be taken into account. An important range of frequencies is that used by echo sounding and sonar devices, typically from about 10 kHz upwards. At these frequencies, cavitation (figure 2.4) is the main source of such noise.
The design of modern propellers intended for noise-reduced vessels generally ensures a low level of this phenomenon up to and including typical survey speeds. At the time that CRR 209 was written, as is still the case, most acoustic surveys had to be run at a speed not exceeding 11 knots because of vessel-radiated noise, and this was the reason for the adoption of that speed in the report. Parameters of echo sounder and sonar systems are well known, so calculation will yield the radiated noise levels that are acceptable at their frequencies of use. This matter is therefore not examined in detail here. However there is some evidence that some fish are affected by emissions in the ultrasound region (see Chapter 3).

2.4 Measurement of Vessel Radiated Noise
In most parts of the world, open water conditions are rarely suitable to allow accurate measurements to be made. However, because it may be difficult to obtain the use of Naval noise range facilities, a measurement standard is currently being developed to provide guidance on how to measure underwater noise in open waters. This will
designate three different standards, namely: Precision, Engineering and Survey Methods. The draft ANSI Standard, “Quantities and Procedures for Description and Measurement of Underwater Noise from Ships” (ANSI S12.64-200X) is currently being formulated. This document will provide a template for underwater measurements carried out at sites other than formal ranges and may be useful as guidance on a measurement methodology that could also be used for Fishery Research Vessels (FRV) when the vessel is being commissioned. However, for vessel acceptance purposes, on a new FRV, it is anticipated that the formal ranges will always be used to quantify the signature to the highest possible degree of accuracy as the outcome often governs financial penalties as well as vessel reject clauses.

Many of the naval ranges currently use the NATO STANAG 1136 (see Box) as a basis for their operations, but parts of this are either open to interpretation, or set requirements that do not fully meet fisheries needs. In some instances the measurement regime depends on the local circumstances of the range. It is therefore necessary to re-examine the results of noise range measurements that have been carried out on fishery research vessels at such facilities, especially as the requirements differ somewhat from those of naval vessels.

**STANAG 1136**

The NATO measurement standard STANAG 1136 sets forward an outline scheme of how underwater-radiated noise measurements should be taken at a range facility.

The general requirements are summarized below:

- Octave band measurements permitted (1/3<sup>rd</sup> octave preferred).
- Frequency range 10 Hz to 80 kHz.
- Narrow band measurements between 10 Hz and 2.5 kHz
- Preferred bandwidth 1 Hz or less.
- Maximum bandwidth:
  - 1 Hz up to a 50 Hz frequency limit; and
  - 3% bandwidth between 50 Hz and 2.5 kHz.
- Beam measurements:
  - Hydrophone depths between a depth of 9 and 36 meters allowed;
  - Plan distance for the hydrophone not less than 100 meters.
Track (or keel) measurements:

- Hydrophone depth not less than 20 meters;
- If water depth 20-60 m, hydrophone to be placed within 1 m of seabed;
- If water depth greater than 60 m, hydrophone placed at 1/3rd of the water depth.

Advise whether Lloyds Mirror effects taken into account.

There are a number of areas where the STANAG standard has limitations and it is believed that a fisheries research vessel ranging should adopt criteria appropriate to the specific issues of need, including fish avoidance. These are discussed in Section 2.4.2.

### 2.4.1 Scope of Present Noise Range Methods

For a vessel, underwater-radiated noise is measured in the far-field of the vessel (typically at a plan distance of 100 m or so from the vessel track and at hydrophone depths of around 30 m). From these far field measurements, the noise is corrected back to a hypothetical source level, at a distance of 1 meter, using a simple hemispherical spreading assumption, i.e., 6 dB change per doubling (or halving) of distance.

For new fisheries research vessels, underwater noise levels are conventionally measured at a formal range as the contract requirements and liquidated damages are often based upon the finally measured signature. In many cases, this will be the only time in the life of the vessel at which its signature is measured. However, it is known that the noise signature deteriorates during the life of a vessel; this can be due to changes in the mechanical condition of onboard equipment as well as the surface condition of the hull and the propeller – which may become subject to fouling (e.g., barnacles, etc). In the case of propellers, even lying alongside for a period of a few weeks can lead to substantial deterioration such that cavitation noise and vibration arises at quite low vessel speeds.
Although the low frequency spectrum starts at 1 Hz (see above), in practice the low frequency limit of 10 Hz is conventionally used on most noise ranges. That is not to say that measurements cannot be taken at lower frequencies. It is simply that such measurements can only be used for comparative purposes because the dimensions of the range then generally become comparable with the wavelength at these frequencies and it is doubtful if the results would be repeatable at other ranges. Some ranges offer a facility measuring down to 1 Hz or 3 Hz. However, because most ranges are necessarily located in sheltered areas, they are of restricted physical dimensions (e.g., at 1 Hz the acoustic wavelength (λ) is approximately 1500 meters, and one or more boundaries of a typical noise range are likely to be much less than this). Results from “Cirolana” (figure 2.6) are an exception.

To cover the range of known hearing of most fish, vessel source levels should be defined and measured up to 5 kHz at a minimum, although this threshold may not adequately address fish hearing in the ultrasound. But the vessel noise signatures also need to be measured at the frequencies of the onboard acoustic systems to ensure that they can function efficiently with low background noise at the operational frequencies. The high frequency limit is normally set by the specification at between 30 and 50 kHz to match the performance of the noise range hydrophones and the overall measurement system, as well as the rapid decay of the pressure wave at high frequency. For example, even light mist can create high background (ambient) noise levels above these frequencies, which affect the ability to measure underwater noise reliably.

Because of the fairly regular rate of decrease of noise above about 1 kHz a certain amount of interpolation can generally be expected for frequencies higher than this. The exception to this is where high frequency flow generated noise is exhibited by well designed cooling systems. In this eventuality, broadband energy may be generated which does not exhibit the same degree of fall-off with frequency. Typically, the use of low flow velocities and long radius bends on cooling water systems will minimize flow noise generation; and the use of flexible bellows on such systems act as attenuators at specific frequencies for pump generated noise etc. due to the impedance mismatch created by the distensibility of the bellows.
2.4.2 Noise Interaction with the Sea Surface
An often neglected factor is the interaction of ship radiated noise with the sea surface. To determine this it is necessary to know the free-field 3-dimensional amplitude and phase characteristics of the acoustic source. Accurate modeling of noise contributions from surface vessels requires that it is necessary to know how to physically describe the source-surface interaction (Weinstein, 1978), matched with the appropriate form of the propagation loss curve, particularly at the lower frequencies.

The bandwidth of measurement is an important factor. It is normal for a $1/3^{rd}$ octave bandwidth to be used, which is useful for comparative purposes but has the effect of hiding narrowband characteristics of the noise, e.g., tones. It is normal practice to also measure narrow band noise on the noise range and the STANAG guidelines are then usually followed.

The STANAG methodology, as detailed above, is not considered totally suitable for current purposes due to a number of criticisms, including:

- Lloyds mirror\(^1\) effects will be very different for different hydrophone depths. Thus leaving a permitted hydrophone depth range of between 9 and 36 meters (which is understood to be due to the range of depths used within the various NATO countries) is considered inappropriate as various different hydrophone depths might be tried by the noise range/shipyard in an endeavour to gain compliance with a given contractual limit (Wood, 2005 – see figure 2.5);

- Lloyds mirror effects will also be different not only for different hydrophone depths, but also different plan dimensions. It is therefore believed that a small range of permitted plan distances should be specified for the hydrophone;

- the keel hydrophone changes from being bottom mounted in a water depth of up to 60 m to a location which is at $1/3^{rd}$ the water depth when this depth is over 60 meters (this gives rise to a sudden discontinuity in location at a depth of ~ 60 m).

---

\(^1\) Lloyds Mirror effects arise due to the reduction of underwater radiated noise created by the cancellation of noise from the actual source (the vessel) and the image source which is 180 degrees out of phase with the vessel. This occurs primarily at low frequency where the source and the image source are separated by a small fraction of a wavelength. But peaks and troughs arise due to constructive and destructive interference effects over the entire frequency range.
Figure 2.5: This is a comparison of overall attenuation losses exhibited due to a combination of Lloyds Mirror effects and hemispherical spreading losses (also identified separately) due to three hydrophone depths (9 m, 30 m and 36 m). The assumed source depth was the same in all cases (viz. 2.5 m) as was the hydrophone CPA* plan distance (viz. 103 m). The graph clearly shows that although the overall attenuation at high frequency oscillates around the hemispherical spreading losses, significant differences can arise at the lower frequencies.

* CPA = Closest Point of Approach

In addition, it is essential that 1/3rd octave band data is acquired, as octave band data is far too coarse; and that the measurement frequency range be lowered from 80 kHz down to 50 kHz. The use of 1/3rd octave bands is general practice at sound range facilities.

It is therefore recommended that the test methodology for a FRV should be amended to tighten up on the hydrophone test configuration. In addition, it is recommended that other vessel aspects that are considered to be most appropriate for FRVs should be specified within new vessel contracts and measured during the course of an underwater noise ranging acceptance exercise.
2.4.3 Directivity of Vessel Noise

Directionality of the radiated noise arises partially because of the characteristics of each piece of machinery and its placement within the hull, and partially from the propeller directivity and screening effects from the hull. Directivity patterns will change with vessel speed due to changes in equipment power and the source strength of the propeller (e.g. whether cavitating or not). They will also change with frequency as well as with depth, i.e. will have three-dimensional characteristics.

Mounting and placement of the various items of machinery within the vessel have a significant bearing on the final noise outcome. Further, there is not only structure-borne noise to consider but also airborne excited underwater noise – which arises in the mid-frequency range (and particularly around 500 Hz). In reality, the machinery location may lead to significant differences in noise levels between e.g., the port and starboard sides of a vessel (figure 2.6).

Figure 2.6. There are marked differences in the measured noise levels between the port and starboard sides of this noise-reduced vessel. These are apparently due to the machinery layout. In the region from 100 Hz to 1 kHz the port side shows significantly higher levels compared to the starboard side.

Internal construction of the hull has an important bearing on conducting vibration from machinery and consequently on the radiation of noise into the water. The main
propulsion machinery, especially diesel engines, are potentially the noisiest source and a ‘stiff’ seating is necessary to control their low frequency vibrations. Vibration isolators or mounts are often inserted between the machinery and the hull mounting to minimize the transmission of vibration to the hull thereby limiting the extent of underwater radiated noise. The complexity of these measures depends on the magnitude of the equipment forces and moments and the locality of the equipment in the vessel. Diesel engines, which often generate the highest force levels on the vessel, need to be treated with great caution due to their potential to radiate high underwater noise levels. This means that diesels are usually rafted i.e. the diesels are isolated from a large heavy and stiff structure, which is in turn isolated from its seating on the hull. However, all vessels adopt a different design measure, which means that there can be much variability from vessel to vessel.

Figure 2.7 shows data obtained by the use of a necklace of hydrophones passed below the vessel and moved along its length. The results in this figure indicate that the actual pattern of pressure levels in the near field is quite complex. However, these contour plots simply define areas of high and low pressure. There can be circulatory flows in the near field where pressure levels and particle velocities are both high but do not necessarily produce sound radiation in the far-field as the two components of the sound field may not be in phase.

It is evident in the contour map that, as expected, the main machinery items, such as the diesel generator sets, are responsible for the most significant contribution to the noise signature. The main engines and generators (gensets) are mounted between frames 41 to 60 on a double isolation system contained within an acoustically insulated compartment outlined in red. The whole area is hooded. The situation clearly changes once the vessel is underway and the main propulsion drive system and the propeller are in operation.
Figure 2.7: This is a comparison of pressure level contours measured at frequencies of 160 Hz and 1250 Hz beneath a vessel of 72m length and 14 m beam. The difference between the two frequencies is quite marked and gives rise to speculation about the far-field pattern of radiation.

That the pressure frequency spectrum is complex can be seen by the sample contours in figure 2.7, where significant changes occur between the distributions of pressure levels from those at 160 Hz to those at 1250 Hz. But it should be emphasized that these measurements do not indicate power flow from the hull, and hence hull directivity. The main way in which power flow could be established would be to measure underwater sound intensity, by means of two phase matched hydrophones separated by pre-set distances. However, a necklace of phase matched hydrophone pairs would be extremely expensive to produce and would still not address the issue of noise radiation from the propulsion drive system.

The diesel engines on this project (RV Cirolana) were each rated at 1100 bhp, with each engine having 6 cylinders and running at a constant 500 RPM with the 3
generators each having a capacity of 700 kW. This vessel had a propulsion motor of 2200 shaft horse-power at 180 RPM and the power speed curve is shown in figure 2.8.

![Power Speed Curve](image)

Figure 2.8. This illustrates the large increase in power needed to attain speeds over 8 knots. At a typical survey speed of 11 knots about 600 shaft horsepower is required for this 72 m vessel.

There should be a strong relationship between the power being used and the radiated noise. This is broadly reflected by the underwater radiated noise measurements from the same vessel at three speeds (figure 2.9), which shows considerable increase in noise above 10 Hz.
This particular vessel was first noise ranged shortly after delivery and then about 10 years later. Results were very similar, apart from slight increases at these low frequencies presumably due to mechanical wear of machinery components. There are no records of beam measurements from “RV Cirolana” but an idea of the differences that can occur is illustrated in figure 2.6 showing results from the port and starboard sides of a 53 m noise reduced vessel.

The question then arises of how the noise levels change along the arc swept out from one side of the vessel to the other. The pressure field presented in figure 2.7 shows this information by looking at the pressure field at a given frame number (and at a given frequency). This gives some information on pressure distribution at various slices in the vertical plane measured perpendicular to the center line of the vessel, which have then been mapped into contour levels. However, as discussed earlier, the near field pressure levels do not necessarily match with the far field radiated pressures measured on the noise range. This approach is therefore considered to be unreliable. However, sound intensity measurements, which utilize the values of both the dynamic pressure and the particle velocity, would be of far more value in assessing radiated
power from near field measurements and could therefore provide information on the machinery radiated power distribution over the hull of the vessel. But once again, this assessment would exclude the very important propulsion drive system and the propeller.

More conventionally, the pressure field in the far field is represented by a plan directivity pattern (figure 2.10). These data were acquired from a de-classified military source that set forward the directivity patterns that were acquired many years ago on a freighter whilst operating at 8 knots (Pomerantz, 1943).

2.4.3.1 The Butterfly Pattern
The propellers dominate the measured sound field, rather than machinery radiated noise, as the highest pressure levels are ascribed to the stern of the vessel. Further, a dip in the noise pattern occurs forward of the bow and also one aft of the stern giving rise to a so-called “butterfly pattern” in the horizontal plane. This shape was ascribed to hull screening forward and the wake field aft according to Urick (1976).

![Figure 2.10 Equal pressure contours associated with a freighter whilst travelling at 8 knots. Underwater noise measured from bottom mounted hydrophones in 12 m of water. Pressure levels are measured in dB re 1 Pa in the frequency band 2.5 – 5 kHz.](image)

The butterfly pattern was also broadly observed by Misund et al. (1996) for frequencies above ~ 125 Hz (see figure 4.2.). Further, due to the pressure minimum observed ahead of the vessel and the strong lobes to both sides of forward, the highest gradients of sound intensity were observed at angles of ~ 20 degrees off the bow to
port and starboard. Aft of the vessel the situation was less clear, with a pressure minimum sometimes noted directly aft (125 Hz) but at other frequencies an apparent increase in dynamic pressure. These measurements were taken on the FRV *Johan Hjort* (classified as “medium noisy” by Mitson, 1993). The hydrophone depths used were 5 and 8 m, which were said to have measured similar acoustic pressure levels. Similar directivity patterns were found at all frequencies by Trevorrow et al (2008) whilst investigating the change in underwater noise during turns on a 40 meter long vessel.

It would appear that a butterfly type of directivity pattern does broadly exist – particularly forward of the vessel - but there are a number of issues relevant to the vessels of today:

- Are these butterfly directivity patterns representative of the patterns that arise when machinery shell plate radiation is dominant i.e. at lower frequencies? (possibly not, based on directivity patterns for the *Johan Hjort*).
- Is this directivity pattern representative of the patterns that arise on typical modern FRVs? i.e. those that are classified as noise-quieted vessels - as such vessels still seem to generate significant avoidance reaction (Chapter 4).
- How does the pattern vary with depth?
- How does the pattern vary with frequency?
- How does the directivity pattern vary with vessel speed? (the expectation being that it would switch from being dominated by machinery excited shell plate radiation at low speeds, assuming a fixed pitch propeller, to propeller excited, cavitation radiation at high speeds).

The issue of vessel directivity is considered to be important as several references (Soria et al., 1996) have cited the fact that fish will, on occasion, swim into the path of the vessel, likely due to the ability to sense the pressure gradient and therefore move towards the dip in the directivity pattern forward of the vessel. However, without detailed knowledge on the directivity patterns of noise-quieted vessels this is difficult to confirm. Because the recent noise-reduced ICES CRR 209 compliant vessels are all based on a similar design methodology, they will likely exhibit quite similar overall directivity characteristics. By contrast, earlier generation vessels, given a
range of propulsion drive systems and propeller designs, may well exhibit quite different directivity patterns.

2.4.4 Vessel Aspect
One other issue that is associated with vessel directivity is how a noise ranging study is usually performed, i.e. which vessel aspect is measured on the range. Conventionally, beam measurements are carried out on FRVs. However, another consideration is whether other aspect(s) should also be measured. These could be measurements looking at the keel aspect (i.e. hydrophones under the vessel track) or bow aspect (i.e. looking at directional noise as the vessel approaches) or stern aspect (i.e. looking at directional noise after the vessel has passed). These different aspects, particularly the keel and bow aspects may be more relevant in terms of scientific operations on FRVs, as many acoustic instruments such as the echo sounders commonly used for stock assessment are downwards looking, and the noise levels encountered by fish in front of and under the vessel are likely more relevant to predicting avoidance responses than noise levels at the beam aspect.

Maximum noise radiation might be expected to arise directly under the hull rather than at beam locations (although several cases have been observed where the reverse occurs) but for many years noise ranges did not report the data from the keel measuring hydrophones, so little knowledge exists of the magnitude from this aspect. Even now there is a reluctance to use measurements from this aspect to classify vessel noise signatures. However, there is no reason why keel, bow or stern measurements should not be specified for a new FRV project providing that the precise measurement conditions are clearly identified. For example, the stern measurement is usually taken to mean the source strength value that is deduced from a noise sample which starts when the assumed noise source is 150 m slant distance from the hydrophone and concludes when the slant distance has increased to 250 m. Similar definitions apply to bow aspect measurements. The keel aspect measurement is usually defined (at UK ranges) from data that are averaged exponentially over a measurement arc +/- 30 degrees from the vertical, when viewed in plan.
2.4.5 Vessel Signature Tonality
Another issue that could well be important to fish reaction is the strength of vessel tone(s) and associated harmonics. Nicholson et al. (1992) found significantly greater haddock catches in fishing trials of the FRV Corystes when smoothing chokes – used to reduce radiated tonal noise – were in use. Bercy and Bordeau (1987) also found commercial catches of tuna were much lower on vessels where major low frequency peaks existed, relative to vessels with smoother (less tonal) characteristics. Strong tonal (or line) components may also cause rapid changes in the orientation and spatial distribution of fish (Olsen et al., 1983).

When estimating minimum reaction distances, it is also important to consider masking and the critical bandwidths in fish (see Chapter 3). Masking implies that noise is affecting the ability of a fish to detect a given tonal level. A critical band is the frequency bandwidth that effectively masks a given tone. However, not all frequency components necessarily promote masking. Critical bandwidths have been measured for both the cod (Hawkins and Chapman, 1975) and the salmon (Hawkins and Johnstone, 1978).

Note that at lower frequencies, e.g., propeller blade rate frequency and its first harmonic (10 and 20 Hz), minimum reaction distance assessments would probably need consider sensitivity to particle velocity. See Chapter 3 (section 3.4.5) for a detailed consideration of infrasound detection in fish.

2.4.6 Vessel Temporal Changes
Another issue that could be important to fish reaction is the strength of irregular sources with respect to time. These could vary from the continuous sources of vibration/noise that may change with load (such as the diesel generators) to those sources which may be on an automatic start-up sequence (such as diesel generators when the power management system dictates; or air compressors when the receiver pressure falls below a preset limit). These sources should produce quite moderate changes in overall noise signature and are thus unlikely sources of significant fish reaction. What might be of more significance is the sudden transient dynamic pressures generated on start-up. As this is something that can readily be measured on
the static noise range, pressure transients should specifically be measured to quantify the peak dynamic pressures that arise on start-up.

2.4.7 Sound Pressure and Particle Velocity

For fish, it is crucially important to distinguish between sound pressure, the feature of a sound that is usually measured, and particle motion, which may be more relevant to the fish (see Chapter 3). When a particle of water is displaced from its mean position there is a temporary increase in pressure. The pressure increase acts in two ways: it restores the particle to its original position, and it passes on the disturbance to the next particle. The cycle of pressure increases (compressions) and decreases (rarefactions) propagates through the medium as a sound wave.

There are two important parameters in this process: the pressure variation with respect to the ambient fluid pressure and the velocity of the particles of water that oscillate about a fixed position. Sound intensity, which is the average rate of flow of energy through unit area, normal to the direction of propagation, is the product of acoustic pressure and particle velocity. A hydrophone can measure dynamic pressure, but measuring particle velocity is not so simple. However, the particle velocity can be deduced from the pressure gradient (the rate at which the instantaneous pressure changes with distance) via the linearised Euler equation.

In an active field, pressure and particle velocity vary simultaneously. When a peak in the pressure signal occurs at the same time as a peak in the particle velocity signal and the two components are in phase then the product of the two signals gives the net intensity. This occurs in the far field, i.e. when the two parameters are measured well away from the source. In this situation the acoustic pressure and particle velocity are linked by the expression:

\[ P = u \, c \]  

(2.1)

where:

\( P \) = acoustic pressure (in Pa, or Nm\(^{-2}\))
\[ u = \text{particle velocity (ms}^{-1}) \]
\[ \rho = \text{fluid density (kgm}^{-3}) \]
\[ c = \text{speed of sound in the fluid (ms}^{-1}) \]

In the far field, the particle velocity can be estimated by dividing the acoustic pressure by the characteristic impedance of the medium \((\rho c)\). The far field broadly starts at a distance \(r\) of:

\[ r = \frac{2}{2} \]

(2.2)

for a monopole source, where \(r\) is the measurement distance and \(\lambda\) is the wavelength. However, for a dipole source this distance increases to

\[ u_r = \frac{(ka)^3 U \left[ \frac{1}{kr} - \frac{2i}{2kr^2} \right] \cos q}{2} \]

(2.3)

In a reactive field the situation is more complex as the particle velocity lags the dynamic acoustic pressure, with the degree of lag rising up to 90 degrees near the source.

### 2.4.8 Monopole and Dipole Sources

Noise from hypothetical and idealized sources are generally termed as monopole or dipole sources. Basically, a spherical monopole source generates a radiating acoustic pressure by the sphere pulsating (i.e. changing its volume with time). This type of source generates an omni-directional pressure field. However, a dipole spherical source generates a radiating pressure field by the sphere oscillating in a given direction. This source can also be regarded as two monopoles of opposite polarity placed very close to each other (distance \(\ll \lambda /\pi\)). The dipole source generates a pressure field that is broadly represented by a “figure 8” with the radiating lobes being in the direction of the oscillating motion and the nulls perpendicular to this direction.
2.4.8.1 Monopole Equations

Harris (1964) sets forward the basic expressions for pressures and particle velocities in the near and far fields around spherical monopole and dipole sources. This analysis, which was developed on the premise that the radius of the sphere (a) was very much less than ($\lambda/2\pi$), sets forward formulae for pressure and particle velocity in both the near and far fields of these sources. For the monopole source, this leads to the following expression for the magnitude of the radial particle displacement ($d_r$)

$$d_r = \frac{\rho (1 + \frac{1}{(kr)^2})^{\frac{1}{2}}}{c}$$

where:
- $r$ = distance from sphere
- $\rho$ = dynamic pressure
- $\omega = 2\pi f$ (where $f$ = frequency)
- $k = 2(\pi/\lambda)$ (where $\lambda$ = wavelength)
- $\rho$ = density of water
- $c$ = speed of sound in water.

Chapman and Hawkins (1973) considered the above analysis in their experiments on the hearing thresholds and critical bandwidths of cod. They used the distance of the sound source (an underwater loudspeaker) to vary the relationship between pressure and particle velocity to demonstrate that cod were sensitive to pressure at high frequency, and particle velocity at low frequency, following a procedure recommended by Harris and van Bergeijk (1962). The loudspeaker can be regarded as being a monopole source as it is generated by an expanding volume and is broadly omni-directional. Chapman and Harris produced a parametric study of equation 2.4 to show the variation in particle displacement against sound source distance, for a monopole source, at various frequencies (figure 2.11).
This figure shows that particle displacement associated with a given sound pressure is much larger for low frequencies and small source separations. As the distance from the source increases (when \( r > \lambda/2 \)) then the displacement is proportional solely to acoustic pressure, at a given frequency, and is independent of distance as given by the plane wave equation:

\[
    d_r = \frac{p}{2 f c}
\]

(2.5)

Particle displacement rises substantially from its far field value as the source distance is reduced, with the effect being most pronounced at the lower frequencies.
2.4.8.2 Dipole Equations

The position of the dipole source, which equates more to noise radiation from a vessel, is far more complex. From Harris (1964) the expression for radial particle velocity is given by

$$u_r = \frac{(ka)^3 U \left\{ \frac{1}{k^2} + \frac{2i}{(kr)^2} \right\} \cos \theta}{2}$$

(2.6)

where:

- $a$ = radius of hypothetical sphere
- $U \cos \theta$ = radial velocity at the source.

When in the far field of the dipole ($r >> \lambda/\pi$ and $kr >> 1$), the first of these three terms dominates; and when in the near field ($kr << 1$) the last term dominates. At intermediate distances there is a complex spatial variation of particle velocity.

In the near field, the radial particle velocity approximates to

$$u_r = \frac{a^3 U \cos \theta}{r^3}$$

(2.7)

Thus the particle velocity increases rapidly, with the cube of distance, as the distance from the source ($r$) is reduced. This means that for a dipole source, the near field particle velocities could be extremely high. In figure 2.12, the variation of particle displacement has been plotted against distance on the axis of the dipole i.e. $\theta = 0$ degrees. The near field expression has been used out to a distance from the source of $\lambda/\pi$ meters and with the far field expression assumed at any greater distances. Due to this simplistic approach, there is then a discontinuity where the central (intermediate distance) term in equation 2.6 comes into play. The values in this figure have been based upon a sound pressure level of 100 dB re: 1 $\mu$Pa (identical to the sound pressure of 1 $\mu$bar used in the Chapman and Hawkins paper – see figure 2.11). It should be noted that, due to the strong increase in particle displacement at small source distances, the particle displacement has been expressed in dB re: 1 Angstrom (or dB re: $10^{-8}$ cm).
Figure 2.12: Variation in particle displacement amplitude with sound source distance for frequencies between 1 and 300 Hz using a sound pressure level of 100 dB re: 1 μPa (dipole source)

It can be seen from this figure that at high frequency (say 100 - 300 Hz) the far field dominates from all distances over 5 meters from the source. But at low frequency (say 1-3 Hz) the near field still dominates at 100 meters. At 10 Hz, the near and far field regions are separated at about 40-50 meters inferring that underwater ranging measurements (which are typically carried out at ~125 meters) are likely to be within the far field of the vessel at all frequencies above 10 Hz. This figure also demonstrates that particle velocities will rise to very high values close to the vessel with the rise in level being strongly governed by frequency. Whilst there is a very strong increase in particle displacement at low frequencies, it should also be noted that the most dramatic increases in level with distance (between near and far field expressions) arise at the higher frequencies. For example, at 300 Hz there is an apparent increase in level of nearly 50 dB over a short distance. However, there are two complications in drawing conclusions from this analysis: firstly, the central term in equation 2.6 may dominate at these intermediate distances; and secondly the analysis is based on the premise that ka<<1, which infers that the monopole size, designated as a in these equations, must be << \( \lambda/2\pi \) (say 0.1 m for 300 Hz). Despite the above reservations, it is possible that high frequency near field effects may also be
of importance for fish avoidance reactions and not just the infrasonic frequency range, as postulated by Sand et al. (2008) in their review of the herring avoidance reaction paper by Ona et al. (2007). However, it is also true to say that these high frequency effects arise only very close to the source.

When the expressions are derived for the dipole source, then a similar relationship is found for the far field pressure as arises with a monopole source – although it should be appreciated that the far field pressure is always less for the dipole source of similar source vibration level (by a factor of \(ka/2\) – and this infers a reduction since the premise of the analysis is that \(ka << 1\)). But since the above analysis is based upon a given pressure of 100 dB re 1 \(\mu\)Pa, the far field particle displacements in figure 2.12 (dipole) match those given in figure 2.11 (monopole). For example, a particle displacement of 0 dB as exhibited at 100 Hz in figure 2.12 equates to a displacement of 1 Angstrom which matches the displacement of \(~1\) Angstrom seen at 110 Hz in figure 2.11.

### 2.4.8.3 Vessel Sources

It should be appreciated that all the foregoing analysis is for a simple spherical source undergoing harmonic motion. In reality, the source is a large vessel that has complex modal patterns – ranging from hull girder type modes at low frequency (where the motion of the vessel approximates to the fundamental modes of a free beam) to the discrete parts of the vessel (such as the aft or forward decks acting as cantilever beams over part of the vessel) through to more localised high frequency resonances of the shell plating between stiffeners. The structural modes of vibration of a vessel are complex, as is the response to the given excitation forces from the onboard machinery. But it is only at the first hull girder mode (typically around 4-6 Hz for most FRVs between 50 and 100 m long) that there can be significant sections of the vessel that are acting most closely as an oscillating body at low frequency. However, most FRVs do not usually exhibit strong hull girder modes due to their “stubby” nature. (Strong hull girder modes are usually exhibited by vessels that have a very regular construction along their length - such as tankers). The main energy that arises in the infrasonic region is that generated by the propeller at blade rate frequency (and possibly its first harmonic). For a large diameter slow running propeller the main
blade rate frequency at 11 knots often arises at ~ 10 Hz (assuming a 5 bladed propeller running at 120 rpm), with the first harmonic arising at ~ 20 Hz.

Finally, it should also be noted that a simple source located a short distance below the water creates a mirror image source (due to the impedance mismatch at the surface of the water) that is in antiphase to the actual source. This further reinforces the likelihood that a vessel will exhibit a dipole type behaviour. However, the theoretical dipole is quite simple compared to a vessel that comprises a mix of relatively small sources (propellers) as well as extended sources (hull girder/shell plate responses) with complex phase relationships throughout. As the physical size of the source increases, then the near field will extend still farther from the vessel than that inferred due to a point source.

It has been postulated (Sand et al., 2008) that when comparisons were made between fish reactions to a noise-quieted vessel (the new G. O. Sars) and an older noisier vessel (Johan Hjort) one possible explanation of the increased fish reaction from the quieter vessel may have been due to vessel displacement (the gross tonnages of these vessels are 4067 and 1828 tons, respectively). A similar statement was made by De Robertis et al. (2008) in connection with the noise-quieted Oscar Dyson (displacement 2479 tons) versus the older and noisier “Miller Freeman” (displacement 1920 tons). This aspect of the vessel’s field characteristics also requires further investigation – both analytically and through practical (scale) measurements.

All the preceding analysis indicates that close to a vessel, the near field particle velocities could well be extremely high. However, since underwater noise is not even measured as a pressure level down to 1 Hz, this is a totally unknown region from the perspective of vessel-radiated noise. There have been limited fish hearing tests to date in this frequency range (e.g., Sand and Karlsen, 1986).
2.4.8.4 Measuring Particle Velocity

There are several evolving techniques for measuring acoustic particle velocity (or displacement/acceleration) including particle image velocimetry (PIV) and laser doppler velocimetry (LDV).

In PIV, the particle motion is detected by an optical method of fluid visualisation where the fluid is seeded with tracer particles (e.g., Taylor, 1976), used to obtain instantaneous velocity measurements and related properties in fluids. The technique uses the Doppler shift in frequency of laser light scattered from small particles suspended in the medium and vibrating with the same amplitude as the surrounding molecules.

Laser Doppler Velocimetry (LDV, also known as laser Doppler anemometry, or LDA) is a technique for measuring the direction and speed of fluids such as air and water. Broadly speaking, LDV crosses two beams of collimated, monochromatic, and coherent laser light in the flow of the fluid being measured. The two beams are usually obtained by splitting a single beam, thus ensuring coherency between the two. The two beams are made to intersect at their waists (the focal point of a laser beam), where they interfere and generate a set of straight fringes. The sensor is then aligned to the flow such that the fringes are perpendicular to the flow direction. As particles pass through the fringes, they reflect light (only from the regions of constructive interference) into a photodetector and since the fringe spacing is known (from calibration), the velocity can then be calculated from the fringe spacing and the frequency of the signal. Thus, once again, the likelihood is that is also a laboratory tool.

One of the few particle velocity measurement systems that has been designed, manufactured and operated successfully in full-scale trials at sea is the Swallow Float system (D'Spain et al., 1991). This system, which is a free drifting neutrally buoyant sensor system, utilizes a tri-axial orthogonally orientated geophone array as well as an infrasonic hydrophone. The two measurement systems provide independent measurements of infrasonic particle velocity and acoustic pressure. The measurement data was found to be extremely compatible once the rotational resonance of the assembly (governed by the restoring torque created due to the center of gravity being
below the centre of buoyancy for reasons of stability) was allowed for. This resonance was quite apparent from data measured by the geophones but not the hydrophones. Thus it would appear practicable to measure infrasound in a deep water environment although at the bottom end of the spectrum, i.e. sub-5 Hz, the background energy rises steeply towards the micro-seismic peak at ~ 0.1 – 0.15 Hz.

In summary, it is apparent that further research needs to be undertaken into infrasonic sound radiated by vessels as well as some quantification of near field effects by measurements in close proximity to operating vessels. Also, the effect of vessel displacement should be analyzed and scale experiments performed to measure acoustic particle motion under various test conditions using techniques such as PIV or LDV.

2.5 Summary

- **Ambient underwater noise.** Ambient noise arises from different sources: physical, biological, and man-made; and can mask the hearing of sensitive fish.

- **Pressure and spectral content of vessel noise.**
  - **low frequency (infrasound)** is taken as below 20 Hz; infrasound from vessels is produced by the propeller shaft/engine vibrations (e.g., a change of a few degrees in blade pitch results in a very large increase in infrasound) and potentially by the displacement.
  - **mid-frequency** from 20 Hz to 1 kHz represents the hearing range of most fish. Among many pieces of equipment producing mid-frequency noise, the most important is the diesel engine.
  - **high frequency (ultrasound)** is mostly due to the propeller and cavitation. Above about 10 kHz propagation of ultrasounds is increasingly restricted by absorption linked to temperature and salinity.

- **Scope of present noise range methods.** Underwater-radiated noise is measured in the far-field of the vessel. Minimum vessel source levels need to be defined and measured up to 5 kHz; the high frequency limit is set at between 30 and 50 kHz.

- **Directionality of vessel noise.** Subject to change with the vessel speed, with frequency and depth, due to 3-dimensional characteristics. Pressure frequency spectrum is complex and significant changes occur in the distribution of pressure
levels at different frequencies. The propeller dominates the measured sound field, rather than machinery radiated noise, as the highest pressure levels are ascribed to the stern of the vessel. A dip in the noise pattern occurs forward of the bow and also one aft of the stern giving rise to a so-called “butterfly effect”; the highest gradients of sound intensity are observed at angles of around 20° off the bow to port and starboard. The noise level may change from one side of the vessel to the other.

- **Vessel signature tonality.** Strong tonal (or line) components may cause rapid changes in the orientation and spatial distribution of fish. When estimating minimum reaction distances it is important to consider masking and the critical bandwidth in fish.

- **Sound pressure and particle velocity.** Fish are sensitive to both sound pressure and particle velocity. Conventional hydrophones measure dynamic pressure but not particle velocity. The latter can be deduced from the pressure gradient via the linearised Euler equation: in an active field, pressure and particle velocity vary simultaneously; in a reactive field the situation is more complex and the particle velocity lags the dynamics acoustic pressure, with the degree of lag rising up to 90° near the source.

- **Monopole and dipole sources.** Particle displacement associated with a given sound pressure is much larger for low frequencies and small source separation. Particle displacement rises substantially from its far field value as the source distance is reduced, with the effect being most pronounced at the lower frequencies. For a dipole source, the near field particle velocities could be extremely high. The dimension of the vessel is therefore of importance and may explain the increased fish reaction from a quieter but larger vessel due to vessel displacement.

### Chapter 3. The Hearing Capabilities of Fish

Anthony D. Hawkins

#### 3.1 Introduction

Fish depend on sound to communicate with one another, detect prey and predators, navigate from one place to another, avoid hazards, and analyse the world around them. Sound is important to fish.
It was known by the end of the 19th century that fish could hear, and the morphology of the fish ear had already been well described by anatomists like Retzius (1881). However, critical experimental studies of fish hearing were not initiated until the early part of the 20th century (see Kleerekoper and Chagnon, 1954; Tavolga and Wodinsky, 1963; Moulton 1963 for historical accounts; and Hawkins, 1986; Fay, 1988; Fay and Popper, 2000; Popper et al., 2003; Ladich and Popper, 2004; Popper and Hawkins 2012).

Investigators have now became acutely aware that human-generated sounds may have a profound effect on the lives of aquatic animals (see reviews by NRC 2000, 2003, 2005; Richardson et al., 1995; ICES AGISC, 2005; OSPAR, 2009), and that fish may be especially affected adversely by sounds from shipping, underwater explosions, seismic exploration, offshore construction, and sonars of various types. There is concern that high-level sounds may have significant effects upon the fitness of fish, affecting their ability to survive, and there is strong interest in reducing the levels of human-generated sounds or at least mitigating their impact. For fisheries researchers there is concern that the noise from survey vessels may be affecting the behaviour of fish, with the potential result of bias in fish population assessment.

The potential effects of exposure to human-generated sounds include the masking of sounds significant to fish, impacts upon communication with conspecifics, changes in behaviour, effects on stress levels and the immune system, effects upon their ability to orientate, loss of hearing, injury to body tissues, and, ultimately, direct mortality. Where fish respond to human-generated sound with behavior that falls within the range of their standard behavioral repertoire, questions may arise over the relationship between their responses and those key features of the stimulus that are driving them. What aspects of the sound are triggering particular behavioral responses? To address this question, we must examine the hearing capabilities of fish.

3.2 Assessing Fish Hearing
The first goal of measuring hearing is to determine the range of frequencies (or bandwidth) that a fish can detect, and then determine the lowest levels of the sound
that can be detected at each frequency (the “threshold” or lowest signal that an animal will detect in some statistically determined percent of signal presentations – most often 50%). The graphic representation of the threshold as a function of frequency is called an audiogram.

3.2.1 Behavioural Techniques
Fishes detect and respond to a wide variety of sounds. The techniques for determining hearing capabilities of fishes are similar to those used in studies of other animals including humans. One way is to present different sounds and simply observe the response. However, although fish often respond spontaneously to the presentation of a sound, such responses commonly diminish with time, especially if the fish are held in captivity. Habituation makes it difficult to present a full range of sound stimuli and fully explore the hearing characteristics of the animal. Various training and conditioning techniques have therefore been developed to ensure that fish will always respond to those sounds that they can detect. Thus, fish are trained to press a paddle, or swim through an aperture when a sound is presented, in anticipation of subsequent reward or punishment (see for example the training methods pioneered by Tavolga and Wodinsky, 1963). Or the electrocardiograph of the fish is monitored and fish are classically conditioned to show a delay in the heartbeat when presented with a sound, in anticipation of a mild electric shock (used extensively by Chapman and his associates Hawkins, Sand and Johnstone – see references below). Once a fish is trained the sound level can be reduced progressively until the animal no longer responds. The threshold for detection may then be bracketed by raising the sound level if the fish does not respond and reducing it when the fish does respond. The thresholds obtained are repeatable and reliably reflect the hearing abilities of the fish but the process is very labour intensive.

3.2.2 Auditory Evoked Potentials
Alternatively, electrical responses may be recorded from the nervous system of fish as a sound is presented. Microphonic potentials may be detected from the auditory hair cells of the ear with an embedded electrode; or an auditory brainstem response (ABR) may be monitored by surface electrodes on the head of the fish, as done with mammals. For fish it is probably more correct to call the latter electrical responses
auditory evoked potentials (AEPs), as not all of them originate within the brainstem (Suga et al., 2006). To detect the potentials short duration “clicks” or “pips” have commonly been applied as sound stimuli and these can have wide frequency content. Thresholds at different frequencies are determined by reducing the sound level until the electrical potentials can no longer be observed against background electrical noise; or frequency response curves may be prepared by comparing the sound levels that yield a given level of electrical response. Typically, the frequency response curves show less dynamic range (are flatter) than those determined by behavioural techniques. Responses may also be obtained to frequencies to which the fish do not respond behaviourally. Perhaps most critically, the thresholds are usually higher than behavioural thresholds, as they are affected by the inability of the experimenter to distinguish very small electrical potentials against background electrical noise, rather than any limitations in the abilities of the fish. Such techniques are easy to apply as the tedium of training fish can be dispensed with. Despite their deficiencies they are widely used for determining thresholds, although they often differ substantially from behaviourally determined thresholds – they generally show less sensitivity. Their particular value is in monitoring changes in auditory sensitivity and for examining damage to the hearing characteristics of fish induced by high levels of sound.

3.3 Sound Stimuli
The surrounding environment has a great influence upon sounds. It is crucially important to distinguish between sound pressure, the feature of a sound that is usually measured, and particle motion, which may be more relevant to the fish (see also Chapter 2.5.8).

The standard way of detecting the passage of a sound is by monitoring the oscillatory change in pressure above and below the prevailing hydrostatic pressure, or the sound pressure. However in fish, as we shall see later, the actual end organ within the ear which responds to sound is driven not by sound pressure but by the oscillatory particle motion, described by the particle displacement or its time derivatives particle velocity and acceleration. Particle motion is aligned along a particular direction, and is therefore a vector quantity, whereas pressure acts in all directions (it is a scalar quantity). In a free, or ideal, sound field the particle velocity can be calculated from
the sound pressure. In most circumstances these conditions do not apply. For example, particle motion declines steeply with distance away from a source for a given sound pressure, and the rate of decline depends upon the nature of the source. The region close to the source, where particle motion is dominant, is called the “near-field.” The near-field can be extensive. At 500 Hz the near-field may extend about 1 m from a (monopole) source and at 10 Hz it may extend more than 50 m from the source. The ratio of particle motion to sound pressure also changes close to reflecting boundaries or impedance discontinuities, including the sea surface and the seabed. It is especially difficult to estimate the particle motion in small tanks in the laboratory, where the fish is effectively surrounded by reflecting surfaces (Hawkins and MacLennan, 1976).

Most experiments conducted through the playback of sounds to fish, and especially those experiments where thresholds are being determined, involve the transmission of pure tones over a range of frequencies. As most sounds can be broken down into a spectrum of pure tones this is usually considered appropriate. Surprisingly few experiments have employed more complex sounds like those from ships, pile-drivers, seismic air-guns and other human-generated sources. This omission may reflect the difficulty of reproducing such sounds adequately by means of conventional underwater sound projectors. Ships are very large distributed sources with strong low frequency components, as are the beam-forming air-gun arrays used in seismic surveys. Pile driving, where steel beams or tubes are driven into the substrate by hydraulic hammers to support structures like bridges or wind turbines, generate sound not only in the water but in the substrate (propagated as ground-roll or Rayleigh waves). In these cases it is difficult to reproduce adequately the low frequency components without distortion, and also to reproduce the sharp rise-times characteristic of the impulsive sounds generated by air-gun arrays and pile-drivers.

Thus, the presentation of measured sound stimuli to fish under experimental conditions presents great difficulties. Fish are generally most sensitive to low sound frequencies where the wavelength often exceeds the dimensions of the body of water that contains the experiment. The sounds are presented in a variety of ways, sometimes with immersed sound projectors, at other times with the projectors in air above the water. With an immersed projector in a small, open, thin-walled container
very large particle motions are associated with quite low sound pressures, and those motions are usually normal to any air/water interface. With an air loudspeaker above the water the sound field consists almost entirely of sound pressure. In general, the relationship between pressure and particle velocity in an experimental tank is extremely complex, and there is no reliable way of calculating the relative levels of the two quantities. Ideally they should both be measured, but calibrated particle motion detectors are not widely available and this is rarely done. Audiograms and sound pressure thresholds presented by different workers must therefore be treated with scepticism unless the sound field has been carefully specified. Relatively few experiments on the hearing of fish have been carried out under appropriate acoustical conditions and the results from many of the measurements made in tanks - and expressed solely in terms of sound pressure - are misleading.

3.4 An Overview of Fish Hearing

As sounds are variations in pressure or motion with time they can be broken down into the different frequency components they contain. Humans can detect or hear sounds over a frequency range extending from 20 Hz to almost 20 kHz. However, there are many different types of sound and it is often necessary to describe their temporal characteristics as well as their frequency characteristics (although the two are not independent). Some sounds start suddenly and are brief, like a thump or bang; others are long or continuous, like the sound from an engine. Some sounds have a maintained tonal quality, while others are rough, irregular and contain sharp transients. Although the frequency spectrum describes the full range of frequencies within a sound it does not fully specify all the characteristics of the sound that are relevant to fish.

As a starting point, it is useful to compare different species of fish in terms of the range of frequencies, or bandwidth, they respond to, and also the lowest sound levels (thresholds) they are able to detect. For the reasons described above, for most fishes there are no empirical data to describe their hearing characteristics. However, several general conclusions can be drawn from the few audiograms that can be considered reliable. In this account we will consider mainly the larger and commercially important marine species.
Fish are sensitive to a rather restricted range of frequencies compared with birds and mammals. Even the most sensitive fish have relatively poor hearing above 2-3 kHz. There are one or two exceptions; some fishes do appear to be sensitive to very high amplitude high frequency sounds, including the ultrasonic frequencies generated by some sonar systems (e.g., Wilson et al. 2009). However, fish are generally most sensitive to relatively low frequencies. Examples of audiograms obtained under carefully defined acoustic conditions are shown in figure 3.1.

By varying the ratio of sound pressure to particle motion in sounds presented to fish, either by means of a special tank, or by varying the distance of the fish from a source in a free sound field (making use of the near-field effect), it has been possible to demonstrate that some fishes, like the plaice and dab (Chapman and Sand, 1974; Hawkins and MacLennan, 1976) and the Atlantic salmon (Hawkins and Johnstone, 1978), are sensitive to particle motion. Other fishes, like the Atlantic cod (Chapman and Hawkins, 1973), Atlantic herring Clupea harengus (Enger, 1967) and catfish Ictalurus (Amiurus) nebulosus (Poggendorf, 1952), are sensitive to sound pressure. The latter species may be more sensitive than the former to sounds propagating in a free sound field, where particle motions are relatively small. Species sensitive to sound pressure also respond to sounds over a wider frequency range.

![Figure 3.1: Audiograms for Atlantic cod (Chapman and Hawkins, 1973), dab (Chapman and Sand, 1974) and Atlantic salmon (Hawkins and Johnstone, 1978), obtained on an acoustic range in the sea.](image-url)
and an audiogram for the catfish *Ictalurus nebulosus* (Poggendorf, 1952) obtained in a specially calibrated tank. All the audiograms were derived using behavioural conditioning techniques and are presented for fish living under free-field conditions. The Atlantic salmon and dab are responsive to particle motion rather than sound pressure, and quite different sound pressure measurements would be obtained from these two species close to a sound source or air/water interface.

Fish have been divided into two groups – hearing specialists and hearing generalists (or “non-specialists”; Popper et al., 2003; Ladich and Popper, 2004) mainly on the basis of whether they have specialisations in their auditory apparatus that enhance their sensitivity and broaden their frequency range. However, both hearing specialists and generalists are distributed through many fish taxonomic groups. The so-called specialists have adaptations (involving acoustic coupling between a gas-bladder and the ear) that may enhance their hearing bandwidth and sensitivity (i.e., lower their hearing threshold) under open sea conditions. They may also have an ability to detect airborne sounds if they are close to the water surface. Some fish like the cod do not fit neatly within either category and many of those fishes that are sensitive to particle motion may be specialists of a different kind. Comparisons of their sensitivity and bandwidth expressed purely in terms of sound pressure may not be appropriate. Such fish may show increased sensitivity to sounds close to air/water interfaces, where the particle motion is amplified, and they may also be sensitive to substrate vibrations. It may be better to think of fish, the most diverse of vertebrates, as having a wide range of hearing abilities. The ears of different species may be adapted to detect sounds in different acoustical contexts.

### 3.4.1 Gadids

The hearing of fishes within the cod family has been especially well studied. In addition to the cod, examined by Chapman and Hawkins (1973), Chapman (1973) has also examined hearing in three close relatives, the haddock, *Melanogrammus aeglefinus*, the ling, *Molva molva*, and the pollack, *Pollachius pollachius* (figure 3.2). Another gadoid of particular interest is the walleye Pollock, *Theragra chalcogramma* that supports one of the largest single species fisheries in the world. Park et al. (1995) measured hearing in walleye by means of classical conditioning and obtained thresholds up to a frequency of 1,000 Hz (1 kHz). The most sensitive frequency was 200 Hz where the mean threshold was just below 100 dB re 1 μPa. This is much less
sensitive than the thresholds obtained for cod by Chapman and Hawkins (1973), and for haddock, ling and pollack by Chapman (1973) and it is possible that the thresholds were masked by high levels of background noise. A more recent study by Mann et al. (2009) using an AEP technique has indicated greater sensitivity (lower thresholds) for the walleye pollock, with thresholds at 100 to 200 Hz being less than 75dB re 1 μPa for 3 year old fish (figure 3.3). The audiogram was similar in shape to that obtained for cod, with a steep fall off in sensitivity above 350 Hz. These discrepancies between the thresholds obtained by Park et al. (1995) and those obtained by Mann et al. (2009) perhaps indicate flaws in the acoustical methods employed by the former.

Figure 3.2: Audiograms for three species closely related to the cod; haddock, ling, and pollack. All three show substantial overlap with each other and with the audiogram for cod. It is likely that at their most sensitive frequencies (up to 250 Hz) all three are limited by the level of ambient sea noise under most circumstances. The three audiograms are from Chapman (1973).

Figure 3.3: Thresholds obtained for the walleye pollock. The lower thresholds (squares) were obtained by Mann et al. (2009) and the higher thresholds (diamonds) by Park et al. (1995). The large
discrepancies between these audiograms for the same species indicate the influence that different experimental techniques may have upon results with fish.

3.4.2 Clupeoids

The hearing capabilities of clupeoid fish - including the herrings, shad, sardine, anchovy, and menhaden – have received much attention as this group contains many of the most important food and fish meal fishes, and some species exhibit unusually broad hearing ranges. Because these fish are especially susceptible to damage during capture, do not thrive in small tanks, and are resistant to conditioning techniques it is extremely difficult to obtain behavioural audiograms. Enger (1967) detected AEPs from herring, *Clupea harengus* in a small tank containing an immersed sound projector. A tentative and conservative audiogram was obtained, indicating that the fish was sensitive to pure tones over the range 30 – 1,000 Hz, falling off steeply above 2 kHz (Figure 3.2). AEP studies on the spotted sardine, *Sardinops melanostictus* in a shallow tank with a loudspeaker in air above the tank showed a rather narrower and much less sensitive audiogram (Akamatsu et al., 2003). Other studies have shown that some clupeid fishes, including shad and menhaden, can detect ultrasound (sound with frequencies higher than 20 kHz) and actively avoid it, perhaps affecting the ability to perform stock assessment using these acoustic methods (Dunning et al. 1992; Nestler et al., 1992). Thresholds obtained by cardiac conditioning of the American shad, *Alosa sapidissima* by Mann et al (1997) show relatively poor sensitivity to frequencies below 1 kHz (although the authors acknowledged that the thresholds may have been masked by noise) but found sensitivity to high level sounds at ultrasonic frequencies (figure 3.4). Similarly, it has been shown that the menhaden *Brevoortia* is capable of detecting sound frequencies from 40 kHz to at least 80 kHz (Mann et al., 2001). In contrast, Pacific herring, *Clupea pallasii* in a shallow tank with immersed sound projectors showed AEP responses up to 5 kHz, but never to ultrasonic frequencies (Mann et al, 2005). Similarly negative results were obtained from other species of Clupeinae; the bay anchovy, *Anchoa mitchilli*, scaled sardine, *Harengula jaguana*, and Spanish sardine, *Sardinella aurita* only detected sounds at frequencies up to about 4 kHz (Mann et al., 2001). It seems that within the Clupeidae only members of the subfamily Alosinae, which include the shads and menhaden, detect ultrasound. There is a need to revisit the hearing sensitivity of the herring and other Clupeidae.
Figure 3.4: Audiograms for clupeid fishes. The audiogram for the herring (Enger, 1967) was based on microphonic potentials (square symbols). That for the spotlined sardine (Akamatsu et al., 2003) was based on AEPs (triangles). That for the American shad (Mann et al., 1997) was based on cardiac conditioning (diamonds).

3.4.3 Elasmobranchs

Audiograms for particle motion have been obtained in five species of elasmobranch fishes using classical conditioning or auditory evoked potential methods (see Casper and Mann, 2009 for a review). Their range of hearing extends from around 20 Hz up to 1 kHz, with similar thresholds in all species above 100 Hz. Below 100 Hz the more active swimming fish-eating sharks appear to have more sensitive hearing. However, in general elasmobranchs do not appear to be as sensitive to sounds as teleosts.

3.4.4 Infrasound Detection

Most audiograms do not provide results for frequencies below 20-30 Hz because of the difficulty in obtaining sound projectors that produce undistorted sounds at very low frequencies. Sand and Karlsen (1986), working with a specially designed tank, have shown that cod have an acute sensitivity to extremely low frequency linear accelerations, or infrasound, extending below 1 Hz. The threshold values measured as particle acceleration decline (i.e., sensitivity increases) at frequencies below 10 Hz, reaching the lowest value at 0.1 Hz. The authors put forward the hypothesis that fish
may utilize information about the infrasound pattern in the sea for orientation during migration. Knudsen et al. (1992; 1994; 1997) later examined juvenile Atlantic salmon, and Pacific salmon, *Onchorynchus* spp. and concluded that frequencies in the infrasound range (5-10 Hz) were the most efficient for evoking both awareness reactions and avoidance responses. Similar avoidance responses to infrasound were also shown by downstream migrating European eels, *Anguilla anguilla* (Sand et al., 2000; 2001). More recently, Sand et al. (2008) have suggested that near-field particle motions generated by the moving hull of a ship are mainly in the infrasonic range, and infrasound is particularly potent in evoking directional avoidance responses. Large vessels, in particular, may generate especially extensive particle motion fields.

### 3.4.5 Masking

Within their relatively restricted frequency range some fish are acutely sensitive to sounds. Indeed, in the sea the cod is often not limited by its absolute sensitivity but by its inability to detect sounds against the background of natural ambient sea noise. Only under the quietest sea conditions do cod show absolute thresholds (Chapman and Hawkins, 1973). Any increase in the level of ambient sea noise, either naturally as a result of an increase in wind and waves or precipitation, or from the passage of a ship, results in an increase in the auditory threshold (a decline in sensitivity). The ability of these very sensitive fish to detect important signals (e.g., sounds from a predator, or the sounds made by conspecifics) will be affected not just by variations in natural ambient noise but will be masked by any extraneous sounds which raise the level of background noise. It should be noted that many of the differences in sensitivity seen in the audiograms of different species may be the result of variable noise levels prevailing under experimental conditions. For instance, aquarium tanks are notoriously noisy.

The sea itself is naturally noisy (figure 2.1, Chapter 2.3). Sounds of falling rain, breaking waves, cracking ice, bubbles, spray and turbulence provide a continuous but a varying background of noise. Less frequently, earthquakes, volcanic eruptions and lightning strikes generate intense sounds, travelling over great distances. Sounds from marine mammals, fish and crustaceans add to the ambient noise. Snapping shrimps and chorusing fish can contribute significantly over a wide band of frequencies, which
may mask communication signals from conspecifics. Together with the sound of wind-driven waves these biological sounds may dominate ambient noise levels. In recent years humans have added to sea noise. Sounds from shipping, underwater explosions, seismic exploration, offshore construction, and sonars of various types have raised the overall level of background noise in the sea.

3.4.6 Sound Discrimination

Behavioural and physiological investigations have shown that fishes are able to discriminate between sounds of different amplitudes (Jacobs and Tavolga, 1967); different frequencies (reviewed by Enger, 1981); detect some sounds even in the presence of background noise; and distinguish between sounds from different directions. These higher level capabilities are important to a fish as they enable discrimination between the sounds of predators and the sounds of prey, determination of the location of potential predators or prey, and the ability to lift sounds out of a noisy background.

Especially important is the ability of fish to separate sounds from background noise by means of a filtering mechanism that operates in the frequency domain. Not all frequency components of the background noise contribute to masking. Hawkins and Chapman (1975) showed that in the cod a pure tone signal is only masked by those frequencies within a narrow band on either side of the tone. Effectively, the cod is able to employ a narrow band filter, which can be tuned to the frequency of a stimulus and which eliminates the masking effects of remote frequencies. This “critical bandwidth” varies with frequency but is of the order of one third of an octave. Figure 3.5 illustrates the filter bandwidths determined for the cod by Hawkins and Chapman (1975) using narrow bands of noise to mask pure tone stimuli.

It must not be concluded from these findings that frequency filtering is the only kind of sound discrimination mechanism that is present in fish. Many of the sounds made by fish themselves have a pulsed structure. Differences between closely related species, or between calls made in different contexts by the same species, often vary in their pulse patterning (Myrberg and Spires, 1972, 1980). It is likely that fish are able
to discriminate between sounds and separate sounds from the noise background on the basis of their temporal as well as their frequency characteristics.

Figure 3.5: A comparison of the relative masking effect of 10 Hz wide noise bands upon pure tone stimuli at different frequencies across the audiogram of the cod (from Hawkins and Chapman, 1975)

We have already remarked that there are no empirical data to describe the hearing characteristics of a wide range of fishes and even where there are data they are often of doubtful quality. It is evident, however, that the anatomy of the auditory system often provides a guide to the hearing abilities of particular species. For example, one of the most important indicators of auditory diversity is the presence or absence of a gas bubble or gas-filled bladder, which is important for the detection of sound pressure.

3.5 The Fish Ear
It appears that the organization of the auditory part of the brain in fish is consistent with that understood for most other vertebrates, and the flow of auditory information from the periphery to the mid-brain appears to be similar (reviewed by Fay and Edds-Walton, 2008).

3.5.1 Hair Cells
The basic mechanism for transduction of sound into electrical signals that interact with the nervous system is the sensory hair cell, which is ubiquitous in the ears of all vertebrates. These cells are typically elongate cylinders, surrounded by supporting cells on a firm connective tissue base. Afferent and efferent neurons, running to and
from the brain, synapse with the hair cells. Each hair cell is strengthened at its apical end by a cuticular plate surmounted by a group of projections, the ciliary bundle, which extends above the surface of the epithelium in which the cell lies (the sensory epithelium, or macula). Many stereocilia, packed with microfilaments, are grouped together, with steadily increasing length towards a longer, eccentrically placed kinocilium containing nine double microtubules and two central single tubules. The positioning of the kinocilium towards one side of the cell gives the apical end of the cell a pronounced structural asymmetry (figure 3.6).

Figure 3.6: The hair cells of the otolith organs are directional in their physiological response to stimulation, having a distinct axis defined by the position of the kinocilium. Adjacent hair cells often have a common axis of orientation

Mechanical stimulation of the ciliary bundle triggers a chain of events that culminate in the release of chemicals, called neurotransmitters, from the cell body that in turn stimulates connected the afferent neurons which send electrical signals to the brain. An important feature of the hair cell is that it is directional in its response to mechanical stimulation. The hair cells are directionally sensitive displacement detectors (Flock, 1965; Hudspeth and Corey, 1977). Depolarisation of the cell and excitation of the primary afferent nerve fibres is most pronounced when the stereocilia are deflected in the direction of the kinocilium, and hyperpolarisation and inhibition of the afferent fibres results when the stereocilia are deflected by shearing forces
acting along the same axis in the opposite direction. The hair cells are often arranged in distinctive patterns within the different maculae of the ear.

### 3.5.2 Otolith Organs

The main sound receptors in fish are the otolith organs of the inner ear (figures 3.7 and 3.8). The ears are paired structures embedded in the cranium on either side of the head, close to the mid-brain. There are no obvious external structures to indicate their presence, although in the clupeid fish there is indirect connection to the exterior via the lateral line system. The morphology and evolution of the ear in fishes has been well described by Coombs and Popper (1982).

![Diagram of the ear](image.png)

**Figure 3.7:** Drawing of the left ear of an Atlantic cod showing the three orthogonally arranged semicircular canals and the three otolith organs, the sacculus, utriculus and lagena.

Each ear is a membranous labyrinth of canals, sacs and ducts filled with endolymph, a fluid with a particular ionic composition and viscous properties. There are three semicircular canals, each incorporating a bulbous expansion, the ampulla, occluded by a jelly-like flap, the cupula. A population of sensory hair cells lies at the base of the cupula. The three canals are arranged orthogonally (at mutual right angles). Angular accelerations of the head cause the endolymph to lag behind the movement, deflecting the cupula and stimulating the hair cells. This sensory system allows the fish to detect changes in roll, pitch and yaw, just as it does in terrestrial vertebrates.
Three sacs within each ear are linked with each other and with the semicircular canals (figure 3.7). One of these sacs, the utriculus, communicates directly with the lumen of the semicircular canals and with them forms the pars superior. The other two sacs, the sacculus and lagena, form the pars inferior. In teleost fishes each of these sacs contains an otolith, a dense mass or stone of calcium carbonate and other inorganic salts (figure 3.8), sitting upon a bed or macula of hair cells. The body of the otolith is separated from the macula but coupled mechanically to it by a thin but layered otolithic “membrane”, into which the ciliary bundles of the hair cells project. The various sacs and their otoliths can vary greatly in size and shape between different species. The sacculus and the saccular otolith are generally the largest, but in the Clupeidae the utriculus may exceed the sacculus in size, while in many Cyprinidae the lagena may be especially large. The utricular macula and the otolith that sits upon it lie predominantly in the horizontal plane, and the saccular and lagenar maculae lie in different vertical planes. Most otoliths have a complex, sculptured shape and appear to have flanges, keels and projections. These differences in shape, together with the enclosing shape of the membranous wall of the sac containing the otoliths, may constrain their freedom of movement. De Vries (1950) pointed out that the saccular otolith is curved; and that it may rotate rather than move along a linear axis. In sharks, skates and rays the maculae of the saccus, utriculus, and lagena are covered by otoconia, a gelatinous matrix of calcium carbonate granules, rather than otoliths (as in terrestrial vertebrates).
Figure 3.8: Reconstruction of the head of a white sea bass, *Atractoscion nobilis* from micro-CT scan images (60 micron cubic voxels), with three pairs of otoliths in lateral view and in dorsal view. Otoliths are white and are magnified below. The cranial bones and soft tissues are semi-transparent gray; the premaxilla and dentary are white. The bones, swimbladder, and soft tissues are not part of the image. Illustration provided through the kindness of Ted Cranford and Carl Schilt.

The macula of each otolith organ is divided into regions, each containing hair cells with their ciliary bundles organised in a particular direction (Dale, 1976). In most fishes the sacculus, for example, has at least four distinct hair cell regions, each organised in a different direction (see review by Popper and Coombs, 1982). Other species have different orientation patterns. The hair cell orientation pattern for the cod is shown in figure 3.9.
Figure 3.9: Hair cell orientation patterns in the left ear of the cod (after Dale, 1976).

Each otolith organ may have many thousands of sensory hair cells within the maculae. Fishes, unlike most tetrapods other than amphibians, continue to produce sensory hair cells throughout much of their lives (Lombarte and Popper, 1994). In addition, there is evidence that fishes, unlike mammals, can replace sensory cells that have been damaged as a result of exposure to certain drugs (Lombarte et al., 1993).

The otolith organs undertake several functions. First, they serve as gravity receptors, enabling the fish to determine its orientation with respect to the Earth’s gravitational field (Lowenstein, 1971). As the orientation of the head changes the otoliths move, deflecting the hair cells. Such a system is also sensitive to linear acceleration, the otolith tending to lag behind as the fish accelerates or overshooting when the body comes to rest. It is also evident that the otoliths play an important role in sound reception.

Pumphrey (1950) suggested that a sound passing through the head of the fish (which has similar acoustic properties to the surrounding water) will move the tissues back and forth, but the dense otolith will lag behind, generating an oscillatory shearing force which will stimulate the hair cells. A simple mathematical model of the otolith and its suspension was put forward by de Vries (1950; 1956). He suggested that the movement of the otolith is critically damped, with a rather low natural frequency of vibration. A critically damped oscillator has a nearly constant response to a broad range of frequencies. However, the amplitude of motion will decline steeply above the natural frequency, causing a reduction in sensitivity to higher frequency vibrations. Sand and Karlsen (2000, 2008) have pointed out that such a system is essentially an accelerometer. The otolith organs are inherently sensitive to the kinetic sound component, particle motion, and not to sound pressure, as confirmed by Chapman and Sand (1974) and Hawkins and MacLennan (1976) for two species of flatfish lacking swimbladders.
3.5.3 Accessory Structures
In many fishes the ear is connected mechanically to accessory gas-filled organs. Gas-filled accessory structures like the swimbladder can assist in hearing because the contained gas is more compressible than the surrounding tissues and water. The pressure changes accompanying the passage of a sound will cause changes in the volume of the organ, which in turn may be translated into an amplified movement of the otolith. The system responds to sound pressure, though the end organ itself is still sensitive to particle motion. Poggendorf (1952), and de Vries (1956) examined the displacement amplification provided by a swimbladder. They concluded that if an appropriate mechanism existed for coupling the movements of the swimbladder to the ear, then substantial amplification could occur over a wide range of frequencies.

Poggendorf (1952), Alexander (1966), and van Bergeijk (1967) went further and suggested that the swimbladder might be capable of stimulating the ear even in the absence of a mechanical linkage. Pulsations of the swimbladder, induced by a sound, might be communicated to the ear directly through the intervening body tissues. Evidence that this occurs in the cod, a species that lacks any direct connection between the swimbladder and ear (figure 3.10), was presented by Enger and Andersen (1967) and Chapman and Hawkins (1973).

Figure 3.10: In the Atlantic cod, the gas-filled swimbladder extends close to the ear, but does not have any specialised mechanical link with it. Nevertheless the cod responds to sound pressure.
Sand and Hawkins (1973) measured the resonance frequency and damping of the swimbladder in intact living cod at different depths and showed that the swimbladder served as an amplifier, transforming sound pressure into re-radiated particle motion with little phase distortion over an extended range of frequencies. Deflation of the swimbladder resulted in a decline in sensitivity to sounds (Sand and Enger, 1973). Remarkably, placing a small, inflated condom close to the head of a dab (which lacks a swimbladder) gave increased sensitivity and extended the frequency range (Chapman and Sand, 1974). However, the swimbladder does not appear to be involved in hearing in all species. Hawkins and Johnstone (1978) showed that salmon (which does have a swimbladder) were sensitive to particle motion over the whole bandwidth. Moreover, deflation of the swimbladder does not change hearing sensitivity in the oyster toadfish, *Opsanus tau* (Yan et al., 2000).

Fish have evolved a number of different mechanisms to acoustically couple the swim bladder (or other gas-filled structure) to the ear, thereby allowing the auditory system to detect the pressure component of the sound field (see Popper et al., 2003 for review). Best known are the Ostariophysans, where the anterior end of the swimbladder is coupled to the ear by a chain of moveable bones, the Weberian ossicles. The functioning of this apparatus was described by Alexander (1959, 1966). Expansion or contraction of the anterior chamber of the bi-lobed swimbladder results in motion of the ossicles. This motion subsequently causes fluid motion in a small sinus filled with perilymph, which is then communicated to an endolymphatic transverse canal connecting with the lumen of both saccular chambers. Motion of the anterior end of the swimbladder causes displacement of the saccular otolith, stimulating the hair cells. Alexander (1959) described adaptations to the swimbladder that allowed the fish to accommodate changes in hydrostatic pressure while still enabling the coupling between the swimbladder and the ear to detect the much smaller sound pressure. An association of diverticulae or ducts from the swimbladder with the ear has also been reported for the families Anabantidae, Balistidae, Chaetodontidae, Cichlidae, Clupeidae, Engraulidae, Holocentridae, Hiodontidae, Megalopidae, Moridae, Mormyridae, Notopteridae, Ophiocephalidae, Sciaenidae and Sparidae (Jones and Marshall, 1953; Alexander, 1966; van Bergeijk, 1967; Braun and Grande, 2008).
In the Clupeiformes there is a very different coupling with the ear, described by Allen et al. (1976). The central feature is a pair of bullae, each divided into gas-filled and liquid-filled parts by a membrane under tension. The gas-filled part of each bullae is connected by a long gas-filled duct to the swimbladder, which acts as a reservoir of gas. Rapid motion of the membrane in the bulla by an incident sound generates motion in the perilymph which is transmitted to the maculae of the utriculus, saccus, and perhaps also the lagena, stimulating the hair cells (Denton et al., 1979; Denton and Gray, 1993; 1998) showed that the membranes in the auditory bullae had flat responses over a wide frequency range from less than 1 Hz to 1,000 Hz, which agrees with the audiogram derived for herring by Enger (1967).

3.5.4. Sound Quality
The means by which fish detect sounds are therefore relatively well understood, but analysis of sound quality by the fish ear is still poorly elucidated. It is necessary to account for the ability of fish to discriminate sounds of differing frequency (reviewed by Enger, 1981) and the relatively narrow critical bands shown by species like the cod (Hawkins and Chapman, 1975). Furukawa and Ishii (1967) distinguished between nerve fibres responding to high and low frequencies in the goldfish ear. However the frequency response of afferent fibers in most of the fish examined is quite broad (Horner et al., 1981). Moreover behavioural studies of sound communication have indicated that fish discriminate between calls on the basis of differences in repetition rate and duration, rather than frequency or bandwidth (Myrberg and Spires, 1972; Fine, 1978; Myrberg, 1981). Fay (1982) has suggested that the auditory system of fish is particularly well adapted for temporal resolution. However, the extent to which fish distinguish sound quality through differences in frequency spectra or fluctuations in amplitude with time is not well understood. Analysis may take place within both the frequency and time domains. What is known is that many of the afferent neurons from the otoliths respond with a high degree of phase locking to the waveform of the sound (Horner et al., 1981; Fay, 1982). Essentially, the waveform of the received signal is coded by the discharge rate of the neurons. Sand (1974) has suggested that the movement patterns of the otoliths may be frequency dependent, and that the parts of the macula that are stimulated may depend upon frequency. However, further studies are necessary before this suggestion can be confirmed.
3.6 Directionality

The ability of fish to discriminate sounds from different directions is equally controversial (see review by Sand and Bleckmann, 2008). Van Bergeijk (1967) originally proposed that the single pressure detector present in many fish (the swimbladder) could not be used to localise a sound source, and that fish therefore could not detect sound direction in the far-field. However, field observations of freely ranging sharks showed that they orientated toward sound sources, often from large distances (reviewed by Myrberg et al., 1976). Moreover, it was subsequently firmly established that teleost fish are able to discriminate between spatially separated sources under far-field conditions, both in the horizontal (Schuijf et al., 1972; Chapman and Johnstone, 1974; Schuijf and Buwalda, 1975) and vertical (Hawkins and Sand, 1977) planes. Indeed, they are able to distinguish between sources at different distances (Schuijf and Hawkins, 1983). This ability not only enables fish to locate the sources of sound but may also assist them in discriminating sounds from a particular source against the general non-directional noise background.

There is strong evidence that the otolith organs themselves can provide a basis for the detection of the axis of particle motion. Experiments by Enger et al (1973) and Sand (1974) provided the first electrophysiological data supporting the notion that fish may detect the axis of particle motion by showing that each sacculus responded in a directional manner to vibrations presented along different angles of azimuth, suggesting that fish might determine the azimuth of a sound source by comparing the output from the two ears. We have seen that the hair cells of the inner ear have a definite axis of sensitivity and there are orderly patterns of hair cell orientation within each macula, suggesting that the axis of sound propagation may be determined by a process of vector weighing. There is also evidence that this pattern of hair cell orientation is preserved at the level of the primary afferent neurons (Fay and Olsho, 1979). Polar diagrams of the directional sensitivity of primary auditory afferents in fish were first presented by Hawkins and Horner (1981), who recorded from the saccular and utricular branches of the auditory nerve in Atlantic cod during whole-body vibrations in the horizontal plane (Figure 3.11).
Subsequent studies have now confirmed these findings for toadfish (Opsanus tau; Fay and Edds-Walton, 1997; 2000), sleeper goby (Dormitator latifrons; Lu et al., 1998; Lu and Popper, 1998; 2001), and plainfin midshipman (Porichthys notatus; Weeg et al. 2002). Thus, the primary auditory afferents in several species from different groups of fishes show directional response patterns similar to the cosine response functions of single hair cells, indicating that each afferent neuron contacts a population of hair cells with the same directional orientation. The afferents from all otolith organs are sufficiently sensitive to respond to particle motions associated with sounds of normal intensity, indicating that the brain may use information from all otolith organs in its analysis of sound. Information about stimulus phase is also conveyed to the central nervous system through phase locking of the afferent neurons. Information from only one ear might suffice for computation of sound source
elevation, while information from both ears might be required for computation of azimuth. Certainly, the peripheral auditory apparatus of a fish certainly appears capable of three-dimensional detection of the axis of sound propagation through vector weighing (see review by Sand and Bleckmann, 2008).

It is still not understood how the directional information in the incident particle acceleration is protected against masking by the amplified secondary particle motions radiating from the swimbladder in those fish that detect sound pressure. Moreover, detection of the axis of particle motion is in itself not sufficient to determine the direction of the sound source, since the particle motion in the far-field is alternately either away from or toward the source. There is an inherent bi-directionality or 180° ambiguity in the vector weighing process, making it impossible to discriminate between opposing sound sources (180° apart). In practice experiments have shown that the ide Leuciscus idus (a cyprinid) can discriminate between opposed sound sources (Schuijf et al., 1977), as can the cod (Buwalda et al., 1983).

The ambiguity is resolved in the phase model for directional hearing in fish (Schuif, 1976; 1981). The model assumes that the fish is able to compare the incident particle movements with the sound pressure, and that by decoding the phase difference between these components the fish is able to discriminate between opposing sound sources. The re-radiated signal from the swimbladder acts as a phase reference to resolve the ambiguity. Certainly, the phase relationship between particle motion and sound pressure is crucial for the fish to be able to perform the discrimination (Buwalda et al., 1983). A number of authors have found this model difficult to accept (see for example Rogers and Zeddies, 2008). Kalmijn (1997) has proposed that this complex model is unnecessary and has suggested instead that fish can make their way to a sound source by simply maintaining a constant angle with respect to the axis of vibration.

3.7 The Lateral Line
The lateral line system is essentially a system for detecting water flow and mechanical disturbances close to the fish (Denton and Gray, 1988). It is found in all bony and cartilaginous fish, the lampreys and hagfish and even the earliest fossil fishes. It
appears as an organized pattern of mechanoreceptors buried in canals, or as superficial organs over the head and body, although there is great structural diversity between fishes (Coombs and Montgomery, 1998). The receptor cells of the lateral line, like those of the ear, are sensory hair cells that respond to shearing forces. Superficial neuromasts are deflected by local superficial water movements, while the neuromasts placed in canals may respond to pressure gradients along the body. In both cases they enable fish to detect and respond to sources of hydrodynamic disturbance in their close proximity.

The lateral line has been shown to play an important role in predator avoidance, prey capture, courtship and spawning, orientation to water currents and station holding in flowing water. It may also be used for spatial imaging and exploration in the absence of vision (Bleckmann, 1994). Dijkgraaf (1963) referred to the lateral line as a “distant-touch” system and pointed to the importance of damming phenomena in front of moving objects in water as well as local water displacements. Recent studies have shown that some fish use their lateral line system to track the hydrodynamic wakes left by their prey.

Local turbulent and hydrodynamic effects involve the bulk transport of the medium at relatively low speeds, often over short distances. In contrast, sound propagation involves a transfer of energy through an elastic medium, at very high speed, over large distances, without any net transport of the medium itself. Although both the ear and the lateral line may respond to the large particle motions in the near-field of a large low frequency sound source the critical difference is that the lateral line responds to movements of water external to the fish’s body, while the inner ear responds to the back and forth motion of the whole body of the fish. In addition, although the sensitivity to particle motion can overlap with that of the auditory system, the hair cells of the lateral line system essentially encode frequencies below about 100 Hz (Denton and Gray, 1988).

Ships and other moving bodies in water, and even stationary bodies in a flow field (e.g. piles in an ocean current) can generate hydrodynamic waves, surface waves, turbulence and wakes that move away from the source. These local water movements may stimulate the lateral line system.
3.8 The Impact of Sounds upon Fish

Our current knowledge of the impact of underwater sound on fish is fragmentary. In particular, knowledge of the auditory capabilities of fish is limited and relies, with a few notable exceptions, on experiments carried out in the laboratory under far from ideal conditions (see above). The presentation of measured sound stimuli to fish under experimental conditions in the sea presents formidable difficulties.

Exposure to high level sounds has been shown to induce hearing loss in a number of fish (Scholik and Yan 2001; Amoser and Ladich, 2003; McCauley et al., 2003; Smith et al. 2004; Popper et al., 2005; for a recent review see Popper and Hastings, 2009). A range of behavioural and ecological impacts have also been observed (see for example Chapman and Hawkins, 1969; Pearson et al. 1992; Skalski et al. 1992; Løkkeborg and Soldal 1993; Engås et al. 1996; Santulli et al., 1999; Wardle et al., 2001; Hassel et al. 2004; Slotte et al., 2004; Doksaeter et al., 2009). Some fish have shown changes in swimming behaviour and orientation, including startle reactions. Schools of pelagic fish dive in response to the firing of seismic air guns, while demersal fish flee from a seismic source across the sea floor. The horizontal and vertical distributions of both pelagic and ground fish change after several days of air gun operations. Fish cease critically important activities such as feeding, and sound production. Catches in sea fisheries decrease both during and after seismic surveys. Some of the behavioural effects are short-term, diminishing after the initial presentation of the sound. Others are longer term and result in fish consistently avoiding a sound source.

So far it has not been possible to grade the magnitude of fish responses against the level and characteristics of the sounds presented. Distinctions have been made between involuntary startle responses; voluntary changes in behaviour; and outright avoidance, in an attempt to separate inconsequential behaviour from responses which may be significant, but behaviour is often species and size specific and depends upon the circumstances. It has been said that sounds that are more than 90 dB above the hearing threshold may cause a strong avoidance response and are therefore especially likely to be harmful. Others have suggested that sound pressure levels of 150 or 160
dB re 1µPa should be regarded as those at which avoidance behaviour is triggered. Although it is more cautious, CRR 209 made the assumption that fish would react significantly to ship noise greater than 30 dB above hearing thresholds from published audiograms (Mitson, 1995). In general, there are very few experimental data to support any of these assertions.

Most concern about adverse impacts has been expressed for activities such as pile driving, or seismic surveys by means of air-guns, where fish are exposed to impulsive sounds at very high levels. In some circumstances there have been attempts to regulate the use of such sources. For example, regulatory authorities have set standards for the use of pile drivers. One such standard stipulates that sound pressure levels must be maintained below 150 decibels (dB) rms (root mean square) with reference to 1 micro-Pascal (µPa) for a minimum of half the impacts or strikes; and peak sound pressure levels must be maintained below 180 dB re 1 µPa for all strikes in areas of potential fish presence. The setting of these standards often has been done in an arbitrary way. In particular, a peak value of 180 dB re 1 µPa seems to have gained wide acceptance as an upper limit, above which fish may be injured or impaired, without clear justification or critical appraisal. Some researchers have emphasized that several factors, including the rise time, the total energy, the duration and the repetition rate are as important as the peak pressure in causing damage to fish. Interim criteria for the onset of injury in fish have recently been set (FHWG, 2008) at a peak sound pressure level of 206 dB re: 1 µPa, and accumulated sound exposure levels (SEL) of 187 dB re 1 µPa²-sec (for fish >2 grams body weight) and 183 dB SEL (for fish <2 grams body weight). The accumulated SEL is a measure of the cumulative energy to which a fish is exposed to over the course of a pile-driving event (less than one day).

One of the questions that must be asked in considering impact from sound is what significance the behaviour shown by the fish is likely to have for their well-being and survival. Is the behaviour costly in terms of energy loss or risk to fitness? Does the behaviour result in the longer-term impairment of survival through displacement from a preferred area, or has the fish be denied access to a key habitat? From a conservation standpoint, the impact of extraneous sounds on individual fish is less important than their impact on populations and ecosystems. There have been attempts
to develop predictive models, based on studies of the disruption to individuals, and examining effects on key life functions like feeding, growth, reproduction and migration. But such models are still in their infancy; for example, the “Population Consequences of Acoustic Disturbance” model (NRC 2005).

Some researchers have emphasized that it is important in determining whether a sound is likely to be detected, or have adverse effects, by passing it through a filter that follows the shape of the audiogram. The use of the dB_{ht}^{species} parameter has been recommended by Nedwell and his associates (Nedwell et al., 2007). Such an approach excludes sound at frequencies that the fish is unable to detect. The approach is not entirely valid because injuries may be inflicted to the fish at frequencies outside its hearing range, and especially by steep rise times and high peak values that are associated with wide bandwidth sounds. Moreover, in terms of detection fish are able to lift sounds from the background noise by auditory filtering (critical bands), both within the frequency and time domain. If there are strong spectral features within a sound or any strong temporal characteristics then a fish is likely to be able to selectively ‘tune-in’ to those features. Even more important is that many fishes are sensitive to particle motion, and the expression of exposure simply in terms of sound pressure may not be appropriate, especially at low and infrasonic frequencies. The particle acceleration (m s\(^{-2}\)), the acoustic intensity (in W m\(^{-2}\)) or even the acoustic intensity over time (Joules m\(^{-2}\)) may be more relevant. It is also important to be aware that very low frequency particle accelerations may be present, and may have an impact.

The intention of the dB_{ht} is to provide an overall weighted level to represent the auditory response by comparing the received sound pressure level in each frequency band with the threshold of detection and then combining all these values into a single number. The dB_{ht}^{species} is therefore similar to the dB(A) value used to represent audible sound levels for humans in air. Using this parameter gives a representative number that can then be linked to the likely response to the received sound. In this way, it may be regarded as a yardstick to compare with pre-established reaction criteria. One of the difficulties that prevents the wider use of the dB_{ht} is the lack of repeatable and reliable auditory thresholds for most species of fish. Moreover, its application relies on assumptions about reaction criteria. There has been an
assumption that levels below the $50 \text{dB}_{ht\text{ species}}$ parameter equate to a low likelihood of disturbance, levels above the $75 \text{dB}_{ht\text{ species}}$ parameter equate to mild avoidance reaction of individuals and levels above the $90 \text{dB}_{ht\text{ species}}$ parameter equates to a strong avoidance reaction. However, there are few ‘dose-response’ data to support these assumptions.

Concern has been expressed by some authors that background levels of sound in the sea are increasing and that fish and other marine organisms may be affected adversely by chronic exposure to sounds, without any single source being responsible. In these circumstances the main problem is the masking of significant sounds by background noise. The range over which sound sources can be detected will be reduced and the ability to discriminate and recognise significant sounds will be impaired. There may be considerable overlap between human-made noise and the sounds important to fish. There is a dearth of information on long-term trends in ocean noise. Routine monitoring of background noise levels is now underway at a number of experimental sites and it may be sensible in the future to set maximum average noise levels for especially sensitive marine sites.

3.8.1 Fish Avoidance of Ships
Ships, including fishing vessels and their trawling gear, may affect the behaviour of fish (Chapman and Hawkins, 1969). Mitson and Knudsen (2003) point out that the power of many vessels using diesel engines means significant levels of noise may be radiated underwater. There is concern that research vessels, in particular, must not cause fish avoidance behaviour when they are deploying survey trawls or applying acoustic assessment methods, where unbiased and fishery-independent estimates of the fish stocks are required. This problem was recognised by ICES with the publication CRR 209 (Mitson, 1995).

CRR 209 provided a graph representing the level above which fish were likely to show avoidance behaviour. Experimental evidence was taken from a number of sources relating to two particular species, the cod and the herring, as these two appeared to be especially sensitive to sound as well as being commercially important species. Reaction distances were noted for fish in response to ships with known noise
signatures and ranged from 200 m to 400 m. It was suggested that these distances were too great for research vessels and would affect the validity of the surveys. Attempts should be made to reduce response distances by reducing the radiated noise levels. It was proposed that fisheries research vessels should be able to approach within 20 m of the fish before provoking a reaction. A low frequency sound level was therefore set for such vessels about 30 and 40 dB above the most sensitive hearing thresholds determined for herring and cod (based on AEP thresholds from Enger, 1967, for the herring and the classically conditioned thresholds obtained by Chapman and Hawkins, 1973, for the cod). Projected to 1 m range this gave a maximum allowable level of radiated noise from a vessel (a mean level of 132 dB re 1 μPa, measured over a band 1 Hz wide, over the frequency range 20 Hz to 1 kHz, at one metre). Fish were not expected to encounter radiated noise 30 dB above their hearing threshold from vessels that met this standard at distances greater than 20 metres.

In retrospect, these proposals were perhaps overly simplistic. There was little recognition of the great variability shown in fish behaviour which prevents definition of a precise “reaction distance.” Ships are large, with sound sources distributed in different positions both within and outside the hull. Moreover, the noise signatures of ships are complex, often containing strong spectral lines or bands, and with a rough temporal texture. They are just the kind of sounds which fish are able to separate out from ambient sea noise. It is now recognised that there is great variability in the response of fish to nearby vessels with changes in the condition and physiological state of the fish at different times of the year, or under different local environmental conditions. Fish are potentially able to react to any noise that is a few decibels above their hearing thresholds. For fish that are susceptible to predation, the sense of hearing may provide their only means for detecting and locating predators at a distance, enabling avoidance. The response of fish to what must appear to be a large distributed sound source will depend largely on the assessment by the fish of the risk posed to its well being.

For cod, at its most sensitive frequencies, an increase above the ambient noise of 3 to 6 dB, measured over one third of an octave, is sufficient to be detected. Such sensitivity will allow most ships to be detected at distances of hundreds of meters and
in some cases thousands of meters. It must be recognised that conventional surface vessels will always produce sounds at distances of 50 to 100 meters which will be capable of being detected by sensitive fish like the cod and herring. The aspiration of building large ocean-going research vessels which are inaudible to fish even at close distances may not be able to be achieved unless extraordinary measures are taken. Thus, it may be sensible to accept that fish will react to survey vessels and to plan surveys with this in mind.

3.9 Summary

- **Sound stimuli.** The surrounding environment has a great influence upon sounds. It is crucially important to distinguish between sound pressure, the feature of a sound that is usually measured, and particle motion, which may be more relevant to the fish. There is no reliable way of calculating the relative levels of the two quantities. Audiograms and sound pressure thresholds presented in the literature must be treated with caution unless the sound field has been carefully specified.

- **Fish hearing capabilities.** Most fish are sensitive to a rather restricted range of frequencies, and have poor hearing above 2-3 kHz. Gadids are sensitive to frequencies up to 1000 Hz and most sensitive to 200 Hz. Clupeids present a highly diverse range of capabilities: herrings are sensitive to tones over the range 30-1000 Hz, falling off steeply above 2kHz; American shad is sensitive to high level sounds at ultrasonic frequencies; menhaden is capable of detecting sound frequencies from 40 kHz to at least 80 kHz; herring and other Clupeinae do not show responses at above 5 kHz. Elasmobranchs display sensitivity to sounds between 20 Hz to around 1 kHz.

- **Infrasound detection:** frequencies in the infrasound range (5 to 10 Hz) are effective in evoking both awareness reactions and avoidance responses.

- **Fish ear:** the organization of the auditory part of the brain in fish is consistent with that understood for most other vertebrates. In many fish the ear is connected mechanically to the swimbladder, which augments hearing and allows the auditory system to detect the pressure component of the sound field. Fish may discriminate between calls on the basis of differences in repetition rates and duration, rather than frequency or bandwidth.
Directionality: fish are able to distinguish sources from different directions and at different distances, and to locate the sources of sound; this assists them in discriminating sounds from a particular source against the general non-directional noise background.

The lateral line: enables fish to detect and respond to sources of hydrodynamic disturbance in their close proximity. Ships can generate hydrodynamic wakes that may stimulate the lateral line.

Fish avoidance to vessels: CRR 209 provided a graph representing the level above which fish were likely to show avoidance reactions, under the assumption that fish were not expected to encounter radiated noise 30 dB above their hearing threshold from vessels that met this standard at distances greater than 20 m. This assumption does not take into account the great variability shown in fish behaviour which prevents definition of a precise “reaction distance.” Fish are potentially able to react to any noise that is a few dB above their hearing threshold.

Conclusion: surface vessels will always produce sounds at distances of 50-100 m capable of detection by fish, therefore it may be sensible to accept that fish will react to survey vessels.

Chapter 4. Fish behavioural responses to approaching research vessels
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4.1 Introduction
The purpose of this chapter is to review what is known about the behavioural responses of fish approached by survey vessels, focusing primarily on the body of work appearing after the publication of CRR 209, as reviews of the work conducted prior to CRR 209 are available elsewhere (Olsen et al., 1990; Mitson, 1995; Fréon and Misund, 1999). In this section, we emphasize studies that provide quantitative estimates of the impacts of fish behavioural reactions on acoustic abundance estimates. Although fish are known to react to a wide range of platforms (e.g. Xie et al., 2008; Stoner, 2008), the discussion is intended to follow that of Mitson (1995) and
thus focuses primarily on large research vessels making acoustic measurements and responses to the vessels themselves rather than the sampling gear.

The first goal of this chapter is to review recent studies to establish the behavioural changes that are triggered by approaching vessels and whether current understanding allows for behavioural reactions to vessels to be predicted on the basis of species or functional group, fish depth or fish state (e.g. spawning vs. non-spawning). We summarise what has been learned about the behavioural changes exhibited by fish when approached by vessels, to establish if predictable and stereotyped behaviours are observed. Secondly, we review direct comparisons of noise-reduced and conventional vessels to evaluate whether the use of noise-reduced research vessels leads to reduced fish avoidance reactions. Finally, we discuss the nature of the stimuli that fish are responding to when reacting to a vessel and the mechanisms that may influence whether fish that have detected the presence of the vessel will in fact react to the vessel.

4.2 Behavioural Changes Triggered by Approaching Vessels
Although fish may aggregate under stationary vessels (Røstad et al., 2006), when fish are observed to react to moving research vessels, the reaction is generally consistent with an avoidance response (Olsen et al., 1982a). Typical reactions are:

- vertical avoidance or diving
- horizontal dilution
- herding
- second order responses to the behaviour of conspecifics

4.2.1 Diving
Diving responses are commonly observed in association with vessel passages, particularly for shallowly distributed fish. Studies conducted on Norwegian overwintering herring show that shallow herring in particular exhibit substantial diving reactions. A mean vertical displacement of up to 40 m has been repeatedly recorded for overwintering Norwegian Spring Spawning Herring (e.g. Vabø et al., 2001; Ona et al., 2007, figure 4.1).
Figure 4.1: The echogram for a single passage over the moored echo sounder when passed by "G.O. Sars" (a) and "Johan Hjort" (b), respectively. The black line is the median depth distribution for this passage, and the blue and red lines are the means of the median depth distribution for all passages in the experiment for "Johan Hjort" and "G.O. Sars", respectively. From about 2 min before passage and to 2 min after passage a median displacement of about 20 and 40 m is seen for "Johan Hjort" and "G.O. Sars", respectively. From Ona et al. (2007).

However, experiments on the same stock of herring when spawning or pre-spawning revealed little evidence of avoidance behaviour, although a direct comparison is not possible as different (and smaller) vessels were used as the stimulus (Skaret et al., 2005; 2006). Diving has also been reported for demersal fishes such as Atlantic cod responding to a trawling vessel in the Barents Sea (Handegard and Tjøstheim, 2005). Walleye pollock have been observed to exhibit diving responses, but these are typically more modest (< 5 m and not more than 15 m De Robertis et al., 2008; De Robertis and Wilson 2010). Gerlotto et al. (2004) reported that Peruvian anchovy, *Engraulis ringens*, and common sardine, *Strangomera bentincki*, showed a moderate diving response (from the surface to 5-10 m depth).
4.2.2 Horizontal Displacement
Lateral avoidance of approaching vessels has been inferred primarily from tracking schools from sonars (Misund et al., 1996), counting the number of detected schools in the athwartship direction (Soria et al., 1996), or tracking individual fish using split beam echo sounders (Handegard and Tjøstheim, 2005). Elevated densities of fish schools are often observed by lateral-looking sonars compared to downward-looking echo sounders (e.g. Pitcher et al., 1996; O'Driscoll, 1998), suggesting that lateral avoidance was occurring. In particular, small pelagic fishes can exhibit strong reactions to approaching vessels, as one might expect for shallowly distributed species. Soria et al. (1996) studied the fraction of anchovy, *Engraulis encrasicholus*, and sardine, *Sardina pilchardus*, schools available to a downward looking echo sounder in the Mediterranean Sea with multibeam sonar and estimated that only 41% of the schools detected by the sonar would be available to the echo sounder due to a lateral shift of fish schools away from the vessel. In contrast, Gerlotto et al. (2004) reported no difference in Peruvian anchovy and common sardine school counts in Chile as a function of athwartship distance, indicating that no lateral avoidance occurred in this case. Ona et al. (2007) used an acoustic doppler current profiler (ADCP) to estimate the mean horizontal movement of the fish layer during vessel approach and passage, but no clear signal was observed.
Figure 4.2. Distributions of radial swimming directions of sonar-tracked herring and sprat, *Sprattus sprattus*, schools with the presumed noise intensity of the vessel in different directions (Misund and Aglen, 1992, their figure 5). The distributions of swimming directions was interpreted to be consistent with fish reacting to the approaching vessel by swimming towards and forward of the vessel path where the intensity of radiated noise is thought to be lower.

### 4.2.3 Herding

Fish well ahead of approaching vessels have been documented to move towards the vessel path (e.g. Handegard and Tjøstheim, 2005; Misund et al., 1996; Soria et al. 1996; Gerlotto and Fréon, 1992; Misund and Aglen, 1992). Vessels produce a non-uniform "butterfly" pattern of radiated noise in the lateral plane with a minimum in front of the vessel and maxima to each side (c.f. Urick, 1983; Chapter 2.5.4). This pattern is frequency dependent, and more pronounced for higher frequencies (Misund et al., 1996). Thus, the movement of fish towards the vessel track is predicted if fish move away from areas of high radiated noise (e.g. figure 4.2), and a reaction pattern similar to the directivity of the vessel's noise field suggests that radiated noise produced in the area of the propeller may be an important stimulus at least at longer ranges. As the vessel gets closer to the fish, the keel aspect directivity of the stimuli will become more important in determining the stimuli detected by the fish (e.g. Olsen et al., 1983b), particularly if radiation from the keel aspect is strong and/or the bottom bounce path is important.

### 4.2.4 Second Order Responses

In addition to the primary stimulus, fish may react to second order stimuli. This is typical for schooling fishes, where individuals may polarize their behaviour (see e.g. Parr, 1927). It is known that fish have the ability to propagate information rapidly through the school (Gerlotto et al., 2006). It is thus possible that entire schools of fish react simultaneously to an approaching vessel. This is typical for the Norwegian spring spawning herring in the overwintering state, where the whole layer reacts (c.f. figure 4.1) to the vessel, but this effect is not seen in walleye pollock, where the shallower fish tend to have stronger reactions (e.g. figure 4.3; De Robertis et al., 2008; De Robertis et al., 2010). The morphology, swimming behaviour and depth distribution of fish schools as a whole have been shown to change in the presence of a
vessel (Gerlotto and Fréon, 1992; Misund and Aglen, 1992). Soria et al. (1996) reported that sardine and anchovy schools were less abundant and more compact near the vessel than farther away, suggesting both lateral avoidance and compression of fish within the schools in response to the approaching vessel.

Figure 4.3. Observations of walleye pollock abundance from buoy-mounted echo sounder as vessels sequentially approach the buoy from a distance of approximately 1 nautical mile until reaching the closest point of approach (CPA) to the buoy (~10 m) then continue this course until approximately 1 nautical mile away from the buoy. A) Example echogram as the conventional Miller Freeman (MF) runs past buoy. B) Example echogram as the noise-reduced Oscar Dyson (OD) runs past buoy. The MF can be seen to disturb the shallowest walleye pollock prior to arrival, while this is not clear for passage of the OD. C) Averaged response for all buoy passes (MF n=7, OD n=6) showing changes in backscatter from a reference period as the vessels approach and pass the buoy. Results are shown for walleye pollock at depths of less than 125 m as the difference is most apparent for shallowest fish. The grey bar shows that the fish begin to respond about 45 sec prior to vessel passage, which is approximately 300 m prior to CPA. Figure from De Robertis and Wilson (2010).
The timing of fish reactions relative to vessel passage appears to be variable. For example, Ona et al. (2007) did not detect change in herring backscatter at the time of vessel passage, but the reaction was stronger after vessel passage (figure 4.1). However equivalent measurements on this same stock have documented reactions occurring well before vessel passage (reviewed in Hjellvik et al., 2008). The timing of the different reaction patterns is important in terms of their impacts on acoustic measurement of fish populations. If the reaction occurs primarily after the fish have been measured by the vessel's echo sounder, the biases on acoustic measurements will be small. Consequently, both the timing and the intensity of the reaction can affect observations from a vessel.

The distance at which fish begin to react to the vessel is also informative as this may help narrow down potential causes for the reactions. In Ona et al. (2007), the diving response started approximately 2 minutes prior to vessel passage. This corresponds to approximately 600 m at the standard cruising speed of 11 knots. Misund et al. (1996) reported schools of herring moving towards the vessel track at distances ranging from 25 to 1000 m in front of the vessel. Longer distances are observed for some demersal fishes from trawling vessels. Engås et al. (1998) used a stationary positioning system to monitor acoustically tagged cod in the pre-vessel zone and observed reaction distances varying from 470 – 1470 m ahead of a fishing vessel. Handegard and Tjøstheim (2005) found that the fish in the Barents Sea reacted up to 15 minutes before the vessel passed. For a trawling speed of 3 knots, this corresponds to 1300 m. This reaction was associated with the initiation of the trawling event, probably caused by the changes in vessel noise during the set and shooting of the trawl, and is not directly comparable to the free running situation. Walleye pollock have been observed to initiate avoidance responses at separation distances of ~ 270 m from a research vessel (De Robertis and Wilson 2010). Taken together, these observations provide substantial evidence that vessel reactions are often caused by rapidly propagating stimuli with low propagation loss such as underwater radiated noise that fish will be able to detect well in advance of an oncoming vessel.

The body of published observations (e.g. Box 5.1) shows that fish can react to approaching vessels. However, one should keep in mind that many of these reports are from situations that are amenable to measurement (see Chapter 5), but which may
not be representative of the population as a whole. For example, observations from a fixed echo sounder to measure fish reactions to approaching vessels can be very informative, but this approach is only practical in cases where fish distributions are very uniform and the perturbation due to vessel passage is much larger than any background fluctuations in abundance (e.g. Vabø et al., 2002; Ona et al., 2007; De Robertis and Wilson, 2010). In many cases, fish do not exhibit such distributions, and if the reaction is different in these more common “unobservable” situations, it is unclear whether published studies will be representative for entire surveys or for the problem in general. In addition, one must also keep the potential of publication bias in mind, as dramatic but not necessarily typical cases of avoidance may be more likely to lead to reports in the literature than null observations.

4.3 Do Noise-reduced Vessels Minimize Fish Reactions?
With the advent of the new noise-reduced vessels since the publication of CRR 209, direct tests of whether noise reduction results in reduced vessel avoidance have been possible. It is important to keep in mind that the radiated noise limit was constructed such that species with sensitive hearing (cod, herring, and also walleye pollock, c.f. Mann et al., 2009) were not expected to encounter radiated noise (specified as sound pressure levels) 30 dB above their hearing threshold at distances of > 20 m. However, the efficacy of this noise-reduction measure in reducing fish reactions to vessels requires confirmation by direct comparison of measurements from noise-reduced and conventional (i.e. not noise-reduced) vessels under conditions representative of those during fish abundance surveys. Despite substantial investments in noise-reduced vessels, surprisingly few such studies have been reported to date.

The first study with a noise-reduced vessel (FRV Scotia) revealed that echo sounder measurements of herring abundance from the vessel were comparable to those from a quiet, and orders of magnitude smaller, autonomous underwater vehicle (Fernandes et al., 2000a; b). This observation demonstrates a lack of avoidance to the noise-reduced vessel, but it is unclear whether the herring would have avoided a noisier conventional vessel in this situation. Only a few studies have simultaneously measured fish
avoidance of conventional and noise-reduced vessels under the same experimental conditions.

Ona et al. (2007) used a submerged stationary acoustic platform to show that contrary to their expectations, herring demonstrated a stronger behavioural reaction when approached by *G. O. Sars*, a noise-reduced vessel, compared to the *Johan Hjort*, a conventional vessel, with much of the reaction occurring after the vessel passage. The herring diving response and the vertical velocity during diving was roughly twice as high for *G. O. Sars* than *Johan Hjort* (figure 4.1; Ona et al., 2007). Despite this difference in behaviour, the acoustic backscatter from the stationary echo sounder at the time of vessel passage was similar for both vessels. In addition, the acoustic abundances from the two vessel echo sounders were similar (Ona et al., 2007). Re-analysis of data from a previous experiment described in (Hjellvik et al., 2008) in which an echo sounder buoy was used to compare reactions to these same vessels supports this conclusion, as there are no obvious differences in acoustic abundance of herring at the time of vessel passage (figure 4.4). In an inter-vessel comparison De Robertis et al. (2008) analyzed depth distributions of walleye pollock detected by both conventional (*Miller Freeman*) and noise-reduced (*Oscar Dyson*) vessels travelling side by side and alternating one in front of the other in the eastern Bering Sea during the summer feeding season. During this daytime survey, similar acoustic abundances were observed from the vessels. A differential depth distribution pattern was observed from the vessels, with the *Miller Freeman* observing pollock as deeper only in the case when the *Oscar Dyson* was in front. Equivalent depth distributions were observed in the other vessel arrangements. This was inferred to be consistent with similar mechanism as that observed by Ona et al. (2007). The observed depth distributions were consistent with a stronger diving reaction to the noise-reduced vessel, again with much of the reaction taking place after the fish had been detected by the echo sounder. Direct measurements of behavioural reactions to the approaching vessels were subsequently made two years later with an echo-sounder buoy, but these measurements did not corroborate this inference (De Robertis and Wilson, 2011). Note that in both experimental cases, the noise-reduced vessel was also much larger than the comparable conventional (older) vessel (Chapter 2.5.9).
Figure 4.4. Direct comparisons of vessel avoidance observed by an acoustic buoy or bottom mounted echo sounder between conventional and noise-reduced vessels as a function of fish depth. The mean and 95% confidence intervals of VA, the ratio of abundance estimates between passage and prior to passage, made by the noise-reduced and conventional vessels is given. Results for herring are for the noise reduced “G. O. Sars” and the conventional “Johan Hjort” (Ona et al., 2007; Hjellvik et al., 2008), and results for pollock are for the noise-reduced “Oscar Dyson” and the conventional “Miller Freeman” (De Robertis and Wilson, 2010).

More recent vessel comparisons in 3 different areas (Shumagin Islands, Shelikof Strait, Bogoslof Island) in Alaska (De Robertis et al., 2010; De Robertis and Wilson, 2010) indicate a different result; in some cases, vessel avoidance is significantly lower for a noise-reduced vessel. These additional comparisons of wintertime spawning walleye pollock revealed that in two areas with shallower walleye pollock distributions (Shumagin Islands, fish depths ~ 100-200 m and Shelikof Strait 200-300 m) the noise-reduced vessel detected ~31% and ~13% higher pollock biomass due to differential fish avoidance behaviour (figure 4.5). The Shumagin study also included measurements from a free-drifting echo sounder buoy, which independently confirmed that pollock performed a stronger avoidance response to the conventional vessel, with the strongest response observed for shallower fish (De Robertis and
Wilson 2010; figure 4.3). In the Bogoslof survey area, where pollock are more deeply distributed (400-700 m), estimates from the conventional and noise-reduced research vessels were not significantly different (figure 4.5). When a difference was observed, the vessel avoidance response decreases with fish depth and is weaker in response to the noise-reduced vessel, which is consistent with a response to radiated noise.

Figure 4.5. Summary of experiments making direct comparisons of backscatter measurements made by noise-reduced and conventional research vessels. The vessel ratio (±95% CI – see De Robertis et al, 2008) describes the ratio in observed backscatter by the noise-reduced compared to the conventional vessel. Experiment 1 compares measurements on overwintering herring by “Johan Hjort” and “G.O. Sars” (Ona et al., 2007), and the rest of the experiments are for measurements of walleye pollock in Alaska by “Oscar Dyson” and “Miller Freeman.” Experiments 2 (De Robertis et al., 2008) and (De Robertis and Wilson, 2011) are for pollock during the summer season in the eastern Bering Sea, while experiments 4-6 are for pollock during the winter spawning season (De Robertis et al., 2010). Results for experiments 2-3 are given for night and day separately as diel differences in the vessel ratio are observed in these cases.

These results are not consistent with the observations from the same vessels in the eastern Bering Sea made over two years (figure 4.5). During daytime surveys of shallow pollock, the two vessels detected similar quantities of pollock, indicating that
there were not strong differences in vessel avoidance during the day. However, there is a strong diel pattern in the Bering Sea, with the noise-reduced vessel detecting substantially higher pollock backscatter, but only at night (figure 4.5). Although the pollock were distributed shallower at night, the change in vertical distribution is insufficient to explain the discrepancy if the depth-dependence of the reaction is the same during day and night (De Robertis and Wilson, 2011). This suggests that pollock reactions to the vessels are fundamentally different during day and night in this environment. This diel difference was not observed in the three other locations where pollock reactions to the same vessels were studied. Thus, the degree to which noise reduction affects acoustic pollock abundance estimates differs in the locations, with a strong diel effect in one location only. The differences cannot be explained by simple factors such as fish depth alone, and the reasons for these differences remain poorly understood.

In summary, the comparisons of noise-reduced and conventional vessels to date provide equivocal results regarding the degree to which noise-reduction of vessels minimizes vessel avoidance. Although the work on walleye pollock indicates that a noise-reduced vessel is associated with decreased avoidance and higher acoustic abundance estimates in at least some situations, the work carried out so far on herring (Ona et al., 2007) has documented a greater avoidance reaction to a noise-reduced vessel than a conventional vessel, with much of the reaction occurring only after transducer passage. Radiated noise is an obvious potential explanation for the cases in which the noise-reduced vessel detected more pollock, but this difference cannot be attributed unequivocally to differences in radiated noise alone as other potential stimuli were not controlled in these experiments. What is clear is that there are vessel effects, and that these can bias abundance time series (Chapter 5). These vessel differences are likely not limited to comparisons of noise-reduced and conventional vessels, as conventionally designed vessels differ widely in radiated noise (e.g. Mitson and Knudsen, 2003) and many other respects.

4.4 Which Stimuli are Fish Reacting To?
The key to understanding vessel avoidance is to identify the primary stimuli that cause fish to react to vessels. In the ICES recommendation for radiated noise, the
primary stimulus causing reaction at distances > 20 m was assumed to be pressure component of vessel noise in the frequency band between 1 and 1000 Hz filtered and averaged into 1/3 octave bands (Mitson, 1995). The CRR 209 linked perception to reaction by assuming that a signal 30 dB above the fish's hearing threshold would cause fish to react to the vessel. However, prior to that time, other hypotheses had been put forward as well. Olsen et al. (1983b) hypothesized different ways the fish could respond to vessel noise, including the sound pressure amplitude assuming spherical spreading, the perceived gradient of the sound pressure amplitude given a vessel speed and directivity pattern of the vessel noise, both including and excluding the movements of the fish as they respond to the stimuli. Other potential candidate stimuli include visual cues, the ship's bow wave and wake, infrasonic particle acceleration, and stimulated bioluminescence (Chapter 2). Although the nature of the primary stimulus causing vessel reactions remains poorly characterized, in recent years, several experiments have been conducted that can shed some light on potential factors.

As discussed above, Ona et al. (2007) show that herring exhibit a larger reaction when approached by a noise-reduced vessel than a conventional vessel. In addition, the vessel comparison estimates of walleye pollock vessel avoidance behaviour cannot be explained by considering sound pressure alone, as the reactions are not easily explained by fish depth (i.e. range to the vessel) alone (figure 4.5). In addition, the diel changes in pollock reactions in the eastern Bering Sea cannot be explained by fish depth (and thus radiated noise) alone (De Robertis and Wilson, 2011). Handegard and Tjøstheim (2005) showed that the reaction of demersal fishes to a trawling vessel is not generally stimulated by the gradual increase in vessel noise. Rather, the reaction is associated with the sudden change in emitted vessel noise (i.e. a high rate of change in the stimulus), probably caused by changing propeller pitch when shooting the trawl, which is consistent with the Olsen et al. (1983b) gradient stimuli, and a strong reaction initiated by the trawl warps after vessel passage. The main warp vibration frequencies were measured to be 7 and 14 Hz, but the signal was not detectable from hydrophones in the water column (see figure 4.6).
Figure 4.6. The figure shows various aspects of the observed mean swimming velocity for demersal fish in the Barents Sea (cod, haddock, saithe and redfish) as a trawling vessel is approaching. The vessel passes at $t = 0$. (a) Alongship herding velocity, with an increase in herding in front of the vessel. The bars are running mean estimates with ($\pm$SE), and the continuous curve is a fitted spline. (b) The horizontal speed. We see a clear increase in horizontal swimming speed after vessel passage, not associated with the increase in vessel noise (gray line in the background). (c) Mean athwartship velocity. (d) Mean vertical speed. (e) Mean vertical velocity. (f) Mean vertical velocity as a function of time before after start of tow event, used to explain the initial diving response, i.e. not associated with the increase in vessel noise as the vessel approaches. From Handegard and Tjøstheim (2005, their figure 5).

Acoustic playback experiments are a useful approach to study behavioural responses of fish to anthropogenic sounds as this allows for controlled experiments (Tyak et al., 2009). Several studies indicate that the information content of the stimulus appears to play an important role in vessel avoidance. Experiments with low frequency sources indicate that fish exhibit strong avoidance responses to low frequency sounds, (e.g. Enger et al., 1993; Sonny et al., 2006, see figure 4.7). Fish are sensitive to low-frequency particle motion (Enger et al., 1993; Sand et al., 2001; Chapters 2 and 3).
and intense infrasound has been used to induce fish avoidance responses to improve fish passage around barriers such as dams or power plant intakes (e.g. Sand et al., 2001; Sonny et al., 2006). This indicates that near-field particle accelerations at low frequency, such as those produced by the strong shaft and blade rate tones produced by the oscillating thrust generated by the shaft and propeller which excite the hull (Urick, 1983; Ross, 1987) may be key stimuli influencing vessel reactions. Sand et al. (2008) suggest that the directionality of near field particle motions should be measured and correlated to the directionality of avoidance responses to test this hypothesis.

Figure 4.7. Echogram showing the reaction of fishes in Lake Borrevann to three successive 30 s, 16 Hz infrasound stimulations repeated every 2-3 min. The echogram is presented using a 40 log TVG, where red represents the strongest echoes. The echo sounder was positioned 27 m away from the infrasound projector. From Sonny et al. (2006).

Doksæter et al. (2009) show that herring do not respond to a towed low-frequency (1-2 or 6-7 kHz) sonar source when compared to silent passes. There is a reaction, but that is probably due to the towed body or towing cable (consistent with Handegard and Tjøstheim, 2005). There is, however a reaction to killer whale playback although the killer whale signal is similar in frequency and modulation with the sonar. This reveals that herring are able to discriminate between “similar” signals, and suggests that avoidance reactions can be very different to what might be considered similar stimuli by a human observer (see also Soria, 1994). More recent experiments on penned herring confirm that herring are likely not to react to specific low frequency sonar sources (Doksæter et al., in press), but showed clear responses when exposed to low frequency sound from an outboard engine although the hearing threshold
corrected exposure level was higher from the sonar. However, Engås et al. (1995) found that herring and cod reacted more strongly to playbacks of vessel noise than smoothed and thus more constant versions of these signals projected at similar levels. The playback experiments of Schwartz and Greer (1984) on Pacific herring support these conclusions as they show that herring showed increased responses to sounds that were more intense, of lower frequency, and more irregular as opposed to more continuous ones.

Koslow et al. (1992) report that demersal aggregations of orange roughy dispersed when a camera was lowered within ~130 m of the aggregations. In addition, a response was observed when a small free-falling iron bar that was dropped from the vessel reached within ~60 m of the aggregation. This indicates that the response cannot be attributed to strumming of the cable used to lower the camera alone, and that behaviour can be elicited by a fairly small stimulus compared to that produced by a large vessel. Although the observation with the bar was unreplicated, this observation is very informative, as many of the stimuli generated by a large research vessel (e.g. low-frequency engine, shaft and propeller blade tones and their harmonics) are not likely to be produced by a small iron bar in free-fall.

In conclusion, the governing stimulus, or more likely, the governing stimuli, remain obscure. Vessel avoidance seems to occur at long ranges well before the vessel arrives: this is consistent with the low propagation loss of auditory stimuli. In addition, the pattern of avoidance well in front of vessels appears to be consistent with the directivity of the radiated noise field produced by a vessel. Radiated noise is likely to be important, but there are indications that factors in addition to the sound pressure levels should be considered. For example, low frequency sounds seem to initiate a stronger response than high frequency noise, and the gradient of the signal, as perceived by the fish, is important. The rate of change, the frequency content, repetition rate, and amplitude of auditory stimuli also appear to affect the degree to which fish respond as well as the absolute level of the signal. Further, noise (defined as sound pressure level) is not the only consideration, as there are examples where other stimuli have been demonstrated to initiate a response. A larger number of potential stimuli (e.g. particle acceleration, hydrodynamic and visual stimuli) as well as their propagation and directionality need to be measured for the various vessels,
especially where clear vessel avoidance differences have been observed, and in particular where our working hypotheses (e.g. the CRR 209 recommendations) are falsified (Ona et al., 2007).

4.5 What is the Link Between Perception and Reaction?
The CRR 209 radiated noise limit was constructed such that two species (cod, herring) are not expected to encounter sound pressure levels 30 dB above their hearing threshold at distances of > 20 m. The “30 dB above hearing threshold” criterion for initiation of vessel reaction was used because it was considered that:

“Evidence is overwhelming that fish show a positive avoidance reaction to vessels when the radiated noise levels exceed their threshold by 30 dB or more” (Mitson ed., 1995, p 18).

This is a key point, as it means that fish will likely be able to perceive acoustic stimuli from compliant vessels at relatively long distances, but that the level of the stimulus will be too low to elicit a behavioural reaction. In other words, CRR 209 does not state that the fish will not react to noise levels that exceed hearing thresholds by less than 30 dB.

The attenuation of the vessel noise at 20 m range is -20log10(20) = -26 dB (assuming spherical spreading). The original CRR 209 assumption is that the vessel noise should not exceed 30 dB above the hearing threshold at this range and beyond. If we do not allow the vessel noise to exceed the hearing threshold, which is much stricter, we further subtract 30 dB and get -56 dB. Assuming spherical spreading, this propagation loss is equivalent to 10^(56/20) = 631 m. This calculation assumes that hearing will not be masked by background noise and assumes spherical spreading in the near-field. A CRR 209 compliant vessel will produce radiated noise that is above the hearing threshold of cod and herring at a separation distance of > 600 m. Thus, the specifications in CRR 209, or for that matter other efforts to reduce vessel avoidance, rest heavily on understanding the link between perception of vessel stimuli and the decision to react to the stimulus, as it will be very difficult to build vessels that produce stimuli that cannot be perceived by fish at the ranges required for unbiased measurement of fish abundance (see also Chapters 2 and 3). Given the mixed results of initial comparisons of noise-reduced and conventional research
vessels, it is worth re-examining this key assumption since the mechanism behind the reaction is likely to be more complex.

Although comparatively little is known about the factors that influence how fish react to approaching vessels, there is a rich literature describing responses to predation risk. Many species have been shown to respond to many types of human-induced disturbances as though these disturbances represent a predator (Frid and Dill, 2002). Vessel avoidance reactions are likely responses to a sensory stimulus perceived as a predatory threat. Thus, studies of how animals react to predation risk may provide a context that can be used to improve our understanding of how fish react when they encounter survey vessels. As described by Blumstein and Bouksilla (1996), the link between perception of a stimulus such as predation risk and an observed behaviour can be separated into three stages:

- **Detection**: Information about the risk is gained by reception of sensory information.
- **Assessment**: Information is processed into an assessment of the perceived level of risk.
- **Decision**: The animal combines this assessment of the sensory information with information about the environment and its internal state to produce a decision that results in observable behaviour.

By definition, the ICES CRR 209 limits on radiated noise are well above the hearing threshold of many fish species (Mitson, 1995), and noise-reduction cannot be expected to eliminate the probability of detection at the ranges over which acoustic measurements are made. Thus, the behavioural response of fish to an approaching vessel depends largely on the assessment of the risk posed by the stimuli from the vessel and the factors influencing the decision to react (see Chapter 6). Framed in this context, the attempt to reduce fish avoidance of research vessels by not exceeding the hearing threshold of fish by 30 dB (Mitson et al. 1995), can be viewed largely as an effort to influence the risk assessed by a fish when it detects a vessel, in order to minimize the probability a fish will make the decision to react to the vessel.
It is difficult to understand how fish assess the level of risk from an approaching vessel. Ships produce a wide range of potential stimuli (c.f. the previous section), and these may influence whether the stimuli received from the vessel are assessed as a threat. One would expect that stimuli more consistent with those generated by a known predator, whose approach appears more direct, more sudden, or more intense, are more likely to be perceived as more threatening (e.g. Ydenberg and Dill, 1986; Doksæter et al. 2009). In addition, environmental conditions affect the propagation of the stimulus and how it will be perceived by fish away from the vessel. For example, weather can influence background noise; and hydrographic conditions, water depth, seafloor topography, and composition will affect sound propagation characteristics, which can affect both propagation of the stimuli and levels of background noise (Chapters 2 and 3). Consequently, the stimuli received by the fish may not be consistent even if a vessel generates a similar signature (Popper and Hastings, 2009).

In many cases, animals engage in anti-predator behaviour in response to stimuli in situations in which there is no actual predation threat (Frid and Dill, 2002; Chapter 6). This suggests that animals are faced with making decisions with imperfect information, and may thus make decisions using “rules of thumb” (e.g. Bouksilla and Blumstein, 1992). For example, intense stimuli consistent with a large approaching object might be assessed as high risk, and this may trigger the decision to perform an avoidance response as large rapidly moving objects are likely to be predators. Pitcher et al. (1996) report that herring schools responded to a rapidly approaching research vessel in a similar fashion as attacks by predators. As reviewed above, responses to vessels are highly stereotyped: for example a diving reaction is almost always observed when fish are disturbed. In the case of fish exposed to a bottom trawl, this diving increases mortality by causing fish to dive into the net (e.g. Aglen, 1996; Hjellvik et al., 2003; Handegard et al., 2003; Handegard and Tjøstheim, 2005). The poor outcome of this decision is consistent with the concept that fish are making the decision to dive based on rules of thumb rather than perfect information.

Animals often perform escape responses when they detect other individuals escaping rather than responding to stimuli from the threat directly (i.e. a rule of thumb of: “if a neighbour's escape response is detected, escape as well”). In this case, fish schools can perform coordinated escape responses with the decision to flee propagated by
neighbours in a school resulting in a “wave of agitation” that transfers information across the school (Gerlotto et al., 2006). Reactions of individuals can be highly correlated, and may depend on fish density, as fish in dense schools are more likely to detect reactions of other members of the aggregation (Pitcher and Parrish, 1993).

When animals perceive uncertain stimuli consistent with predation risk, there is strong pressure to make decisions rapidly based on imperfect information. Delaying a decision to escape in order to gain a better assessment of the risk is often associated with a high cost: not reacting to a predator greatly increases mortality when predators are actively hunting. Additionally, the consequences of failing to react to increased risk are highly asymmetric: a poor decision leads to death, whereas the cost of a false alarm is the energetic expenditure and the time lost for other activities such as feeding and mating. Thus, erring on the side of caution when faced with imperfect information about predation risk is expected to be advantageous (Bouksilla and Blumstein, 1992). Strong avoidance responses are expected to be most common for intense but infrequent stimuli (Lima and Bednekoff, 1999), as there is high uncertainty, but comparatively little downside to a strong reaction in this case. In many fish populations, short-range encounters with vessels produce intense stimuli that occur infrequently, and vessel approach is thus likely to elicit strong reactions.

Many factors related to environmental conditions or internal state such as feeding history, maturity state, parasite load, or exposure to predators have been shown to affect the decision-making of fish and other organisms under predation risk (reviewed in Lima and Dill, 1990; Millinski, 1990; Lima, 1998). For example, feeding history and recent history of encounter with predators are well known to affect anti-predator behaviour: hungry organisms, those with a higher parasite load, and those with little recent exposure to predators tend to be less risk averse and less vigilant.

As reviewed above (see also Box 1, Chapter 5), there is evidence that the degree to which a species of fish reacts to vessels depends on the time and place of the experiment as well as the species and its depth distribution. The work on herring suggests that physiological state may play a role: overwintering herring appear to be more reactive than feeding or pre-spawning herring (Fernandes et al., 2000a, b; Skaret et al., 2005; Hjellvik et al., 2008). However, these studies may not be directly
comparable as the vessel used for the non-spawning measurements was substantially smaller than the ones used in the overwintering studies (see Chapter 2.5.9), and may have produced a weaker stimulus. During the day, walleye pollock appear to be more reactive during the winter when spawning occurs than during the summer (De Robertis et al., 2008; De Robertis et al., 2010). In the summer, the vessel differences in backscatter measurements indicate that pollock are much more reactive to approaching vessels at night than during the day (De Robertis and Wilson, 2011). In contrast, the reactions in the other areas during the winter were similar during day and night. Together, these studies are consistent with the idea that factors such as environmental conditions and the internal state of the fish (e.g. physiological state of the fish, recent experience to predation risk or fishing pressure) differ among survey areas and thus affect the strength of the vessel reaction exhibited by a given species.

Vessel avoidance can likely be better understood in the context of how fish assess signals from predators and how they make the decision to flee based on these assessments. It may be possible to formulate simple trade-off models (e.g. optimal escape theory: Ydenberg and Dill, 1986), and test the ability of these models to predict avoidance reactions. The trade-offs between predator avoidance and other activities such as feeding, mating and habitat choice are well known, and this body of knowledge has produced a series of generalizations that if applicable to vessel-fish encounters as a form of predation may serve as a basis to improve our understanding and our ability to improve predictions of vessel reaction (see Chapter 6).

The available studies indicate that our ability to predict vessel avoidance and its effect on fish abundance measurements remains poor. There is a substantial unexplained variability in the timing, strength and characteristics of documented vessel avoidance reactions (c.f. Box 1, Chapter 5): for example, the basic character of spatial and diel differences in pollock avoidance responses or the responses of herring to the G. O. Sars discussed above could not have been predicted a priori based on existing knowledge. The models proposed to predict vessel avoidance (Olsen et al., 1983b; Mitson, 1995) consider only the strength of the stimulus and the ability of an organism to perceive the stimulus, but not the factors affecting the decision to react. It is clear from the available data that these considerations are insufficient to predict avoidance responses with much certainty. It is likely that the factors affecting the link
between perception and reaction must be considered for a more general model, which will require a substantial effort. Unless a substantial increase in understanding of the underlying processes is achieved, this approach is unlikely to provide sufficient precision to correct survey measurements. For the more modest purpose of characterizing the impacts of vessel reactions on abundance estimates and correcting survey abundance measurements for the effects of vessel avoidance, it may be more tractable to measure behavioural reactions to the vessels or the consequences of these behaviours on abundance measurements.

4.6 Summary

- Vessel reactions are stereotyped, with disturbed fish often diving towards the seafloor.
- Vessel reactions are highly variable in magnitude, with the largest reactions observed for shallower fish.
- The small body of published work suggests that noise-reduced vessels elicit weaker fish reactions in some cases, but not in others.
- The stimuli causing reactions and how they are assessed by fish remain poorly understood.
- The link between perception and reaction is a key unresolved issue. Vessel reactions can likely be better understood in the context of decision making under predation risk.
- Ona et al. (2007) conclude that reducing vessel noise as defined in CRR 209 may be necessary but is not a sufficient measure to eliminate vessel reactions. This review of the available evidence supports this view.

Chapter 5. Effects of Fish Avoidance on Measurement and Assessment

Nils Olav Handegard, Alex De Robertis, Emma Jones, Martin Dorn and John Simmonds
5.1 Introduction
Variability in fish avoidance of survey vessels creates uncontrolled biases in abundance estimates (Freon and Misund 1999). Horizontal avoidance moves the fish out of the acoustic beam, and vertical escape influences the tilt angle and reduces the volume of the swimbladder, and thereby decreases the horizontal projection area and backscatter strength.

In some situations fish show negligible avoidance, such as when schools of fish are located at depth or when they are in less responsive physiological states. This offers no general method for all fish populations, but should be utilised when available. Life histories and spatial distribution data should therefore be scrutinised to identify such optimal temporal/spatial observation windows.

It is the variation in response rather than the absolute strength of avoidance that constitutes the most serious problem. A constant tendency to avoid does not influence relative indices of abundance and could also be compensated for more easily. Seasonal and/or diel periods with large variations should therefore be identified and potentially excluded from survey schedules. For instance, when approaching spawning, the shape of a herring school changes markedly from one day to another, reflecting daily changes in the multiple trade-offs between avoiding predators, spawning and feeding (Axelsen et al. 2000). Large and rapid variations in vessel avoidance may be expected during such transition periods. The acoustic abundance indices of overwintering herring are three times lower at night than during day-time, primarily connected to a more shallow distribution and stronger avoidance of the fish during the night (Vabø et al. 2002). In some cases, surveys may be restricted to daytime, when many pelagic fish tend to stay away from the surface.

Acoustics can be used in a number of ways for fish stock assessment; the most common is echo-integration from vertical echo sounders. This method provides absolute abundance estimates or indices of fish density that can be used as input to stock assessment models (MacLennan, 1990; Simmonds and MacLennan, 2005). In addition, acoustics can be used to map schools (Misund et al., 1996) and count individuals using both vertically and horizontally oriented systems (Mulligan and Kieser, 1996; Mulligan and Chen, 1998). This chapter addresses the impact of vessel
avoidance on echo integration (the most common acoustic method used in fish stock assessment). The influence of vessel avoidance on estimates by other methods of abundance estimates will be broadly similar.

5.2 Echo integration

The echo integration method has become a standard within the fisheries acoustics community (MacLennan, 1990; MacLennan and Simmonds, 2005). The method requires calibrated echo sounders and integrates the total backscattered energy from the full water column, or, alternatively, from a given depth interval. The unit is usually given in “nautical area scattering coefficient” (NASC), or \( s_A \) (m\(^2\)/nmi\(^2\)), which has become a standard in the fisheries acoustics community (MacLennan et al., 2002). A prerequisite for the method is that the targets are, on average, randomly distributed within the echo beam, which allows an equivalent beam angle with constant sensitivity to be applied (MacLennan, 1990).

Calibrated backscattered echo energy is assigned to species on the basis of previous experience, trace characteristics, (i.e. how the acoustic image looks), and trawl sample composition, where the latter can also be affected by fish behavior (see below). To convert the species-assigned acoustic-energy \( s_{A, \text{species}} \) to fish area density, the backscattering coefficient (\( \sigma_{bs} \)) is required. This simply scales the acoustic energy to number of fish per unit surface of the layer

\[
\sigma_a = s_A < \sigma_{bs} >, \text{ (nmi}^2\text{)}
\]  

(5.1)

where \(< \sigma_{bs} >\) is the expected value of the backscattering coefficient. The backscattering coefficient is usually given in logarithmic values,

\[
\text{TS} = 10\log_{10}(\sigma_{bs}), \text{ (dB re 1m}^2\text{)}
\]  

(5.2)

and denoted target strength (TS). The TS depends on the species, size of the individual, tilt angle (i.e., vertical avoidance and behavior), pressure (measured as depth), body condition, and a range of physiological factors (e.g., swimbladder inflation, etc.). In most cases, the TS equation for a species is given as a function of...
length only, although other parameters are sometimes used (e.g. Ona, 2003). In the context of vessel avoidance, depth and behavioral dependence are particularly important.

If \( < \sigma_{bs} > \) is applied and fish density is expanded to the area of the survey, results can be expressed as absolute abundance for a region or domain. If there are uncertainties regarding the correct value of TS to apply, indices may be assumed to be linearly related to the true population. In this case, TS is considered unknown, but assumed to be constant among years. In either approach, systematic errors such as those associated with vessel avoidance will impact the validity of the estimates (Aglen, 1994; Simmonds and MacLennan, 2005). The extent of the impact will depend on the way the data are used to infer abundance.

5.3 Influence of Fish Avoidance on Echo Integration

Several experiments have been conducted to characterize impacts of vessel avoidance (Box 5.1), investigating the change in acoustic backscatter \( s_A \), either as difference in acoustic abundance estimates relative to an assumed undisturbed state, or as comparisons of conventional and noise-reduced vessels. Quantitative measurements have been published for herring, capelin, *Mallotus villosus*, anchovy and sardine, walleye pollock and Antarctic krill, *Euphausia spp.*. Although these studies employ diverse methods (e.g. buoy-mounted echo sounders, moored echo sounders, multibeam sonar, vessel to AUV comparison), they all produce replicated estimates of vessel avoidance, generally expressed as the ratio of the abundance observed by the vessel to the undisturbed abundance. Together, these studies indicate that reaction to vessels can introduce substantial bias on acoustic and trawl-based abundance estimates (e.g., as much as a 64% (Box 5.1) reduction in undisturbed abundance during vessel passage), with the largest biases occurring in cases where the fish are more shallowly distributed (< 120 m depth). It should be stressed that results are highly variable, even within a species, making standard environmental and/or species corrections difficult-to-impossible.

Both the timing and the intensity of fish reaction to the vessel is clearly important to the impact on acoustic measurement of fish populations. For example, if the reaction
occurs predominantly after the fish have been measured by the vessel's echo sounder, as has been demonstrated for noise-reduced vessels in some cases (Ona et al., 2007), the biases on acoustic measurements will be small. However, if the reaction occurs earlier relative to the time of vessel passage, a greater difference compared to the undisturbed backscatter would be expected. Thus, if small changes in the motivation for reacting initiates earlier (later) avoidance, this may translate into major differences in apparent abundance (c.f. Chapter 4). If the degree and/or timing of fish reaction is variable among years, annual effects will be introduced in the survey data, affecting the estimates both when used as absolute and as relative indices of abundance.

5.3.1 Lateral Avoidance
Lateral avoidance is a concern for acoustic measurements by echo sounders as even modest displacements can impact the probability that fish will be detected, as the acoustic beam is narrow and most sensitive in the vertical direction, directly under the vessel. If reactions to the vessel cause the fish to have a non-random distribution within the beam this will bias the echo-integration results, as the echo-integration method assumes that the organisms are - on average - randomly distributed in all parts of the beam (MacLennan, 1990; Simmonds and MacLennan, 2005). For example, the angular half power points (1-way) of a typical echo sounder are approximately 3.5 degrees; thus fish at 100 m depth need only move ~ 6 m from the centre of the beam to be located outside of the nominal beam width. Given that: (1) fish can react well before the vessel arrives, and (2) the beam widths are small compared to the distances fish can travel, bias due to horizontal displacements from the vessel is potentially very large. Conceivably, almost all of the fish could move out of the volume sampled by a narrow echo sounder beam. Examples of observed horizontal avoidance are documented in Chapters 4 and 7.

5.3.2 Vertical Avoidance
Diving influences the survey results primarily through changes or uncertainty in the selection of appropriate TS, leading to potential bias in absolute abundance estimates or additional variability in indices of abundance. There are two main mechanisms: changes in depth and changes in orientation. If the increase in depth is substantial, as for Norwegian spring spawning herring reacting to survey vessels (Ona et al., 2007),
swimbladder compression will alter TS. For example, if herring dive from 50 m to 90 m depth, an 11% reduction in backscatter is expected if typical parameters from herring are used (Ona, 2003).

If fish are already close to the bottom, a diving response may result in entering the acoustic dead zone, or the distance off the seabed where the echo sounder is not capable of discriminating between the bottom signal and the true bottom (see e.g. Ona and Mitson, 1996). If the fish enter this zone, they will not be observed and this will result in reducing the observed acoustic backscatter from the fish. This effect is most extreme for layers just above the seabed. Conversely fish close to the surface - above the minimum depth for normal measurements - may dive to a depth where they can be included in the estimates.

The observed backscatter from a fish aggregation is the convolution of its tilt angle distribution and the backscattering coefficient for different incident angles. If the presence of the vessel causes the tilt angle distribution to change, either by a general diving response (e.g. Ona et al., 2007), or by polarization as fish are herded ahead of a stimulus (e.g. Gerlotto et al., 2006), the change in tilt can cause a change in the TS distribution (e.g. De Robertis and Wilson, 2010). This effect is most often associated with diving behaviour, but other avoidance responses may also be involved. Maximum target strength is observed with the swimbladder near horizontal, in many species with the head tilted slightly down (e.g. Nakken and Olsen, 1977; Foote, 1985; Hazen and Horne, 2004). Thus backscatter has the potential either to increase or decrease, depending on the change in tilt angle at the time of measurement. In some cases, a small increase in backscatter strength is seen prior to vessel passage (e.g. Vabø et al. (2002), their figure 3), which is consistent with an increase in TS as fish alter their tilt angles as they begin to dive.

**5.4 Influence of Avoidance on Trawl Sampling**

In addition to the direct influence of avoidance reactions on estimates of acoustic backscatter, avoidance and selectivity of trawl sampling gear can impact the acoustic estimate. Non-representative sampling will lead to incorrect allocation of acoustic energy to species and size groups. Trawl sampling has inherent biases, as
vulnerability to capture depends on type of gear, species, fish size, and sensory and swimming capabilities as well as environmental conditions. The combination of vessel and trawl avoidance (whole gear selectivity) may result in the trawl catch not being representative of either the undisturbed population or the acoustically sampled population. Incorrect species allocation can lead to bias in the allocation of acoustic energy to species and, consequently, application of the wrong TS relationship. If the length distributions estimated from the catches are biased, this will lead directly to bias in acoustic estimates of numerical abundance (via bias in $<\sigma_{bs}>$), as well as biases in the size (and thus age) structure of the population (via bias in the trawl-derived size distribution used to partition the acoustic signal to size and age classes).

Trawling vessels generally produce higher radiated noise (5-15 dB) due to the heavier strain on the propeller (Chapman and Hawkins, 1969; Mitson, 1995) and also from the machinery involved in trawling itself. Observations of gadoid reactions towards a bottom trawling vessel show that diving movements occurred in the pre-vessel zone in response to the start of trawling activity, but the strongest reactions were herding in relation to the trawl warps (Handegard and Tjøstheim, 2005). More recent modelling of the effective sampling volume of a demersal trawl indicates an effective fishing height of 20 m for demersal fishes in the Barents Sea, but also lateral avoidance of fish in the path of the net (Handegard and Tjøstheim, 2009) which is likely to be a result of avoidance due to both acoustic and visual stimuli. A number of studies have compared acoustic backscatter from free-running and trawling (both demersal and pelagic) vessels with contrasting results. Herring (Misund and Aglen, 1992) and walleye pollock (De Robertis and Wilson, 2006) showed greater avoidance reactions towards vessels towing pelagic trawls. The latter study also reported greater avoidance when using a bottom trawl and observed no difference in vertical distribution of fish beneath a trawling and non-trawling vessel. In contrast, Hjellvik et al (2007) found acoustic backscatter of demersal fish around 12% higher over the whole water column during trawling compared to a free-running vessel and von Szalay and Somerton (2009) reported that the acoustic backscatter for walleye pollock was significantly greater for a bottom trawling vessel in the layers above and below the headrope compared to free-running vessels. Whether the newer generation noise-reduced vessels have altered trawling efficiency compared to conventional vessels has yet to be established. Delayed diving reactions, “startle responses” such as those
observed by Ona et al (2007) may or may not influence subsequent reactions to trawl gear components. Alternatively, changes in the vertical distribution compared to conventional vessels may potentially change availability to a sampling trawl.

5.5 Influence of Vessel Avoidance on Stock Assessment

The influence of potential bias in echo integration abundance estimates on stock assessments depends on the manner in which survey data are used. In direct assessments, (e.g., for capelin - Gjosaeter et al., 2002) and assuming appropriate target strength, the absolute abundance expressed in biomass is taken to be an unbiased estimate of stock size at the time of the survey. If a reliable estimate of natural mortality is available, this estimate may then be used in a projection model to obtain predicted stock size at other times of year, as well as potential yield. Either total biomass or an estimate of numbers-at-age could be treated in a similar manner.

More commonly, acoustic surveys are used to fit stock assessment models, which may be either Virtual Population Analysis (VPA) or statistical age or length-structured models. Current implementations of these models are designed to integrate both fishery-dependent data with multiple sources of fishery-independent data in a statistical approach to population estimation. Acoustic surveys are one of many data sets that could be incorporated in the final estimate.

In VPA models, catch-at-age estimates are used to follow each cohort. Assuming that catch-at-age is without error and assuming a reliable value for natural mortality, VPA gives a description of the past when converged, i.e. when the cohort is no longer part of the population. Acoustic survey indices are used to provide information about the most recent (higher uncertainty) years, consistent with the converged VPA estimates. For example, in the North Sea herring assessment in which VPA models are regularly used (Simmonds 2009), the acoustic biomass estimate is used in conjunction with trawl composition data to obtain a set of indices of abundance-at-age, one index per age class. The VPA is fit to all the indices, each scaled to the magnitude of recorded catch.
One method to evaluate the potential magnitude of vessel effects, including avoidance, is to examine year effects in the converged section of the VPA. Although it is not possible to differentiate between avoidance effects and other vessel effects, the magnitude of all errors taken together can be ascertained. The absence of trend and relatively small year effects with respect to other survey methods can be taken to indicate useful consistency in the survey. For example, for North Sea herring, the acoustic survey provides the most consistent estimate of herring abundance-at-age as compared to trawl surveys which require more vessel days (Simmonds 2009).

A second class of models is statistical age-structured models, where model fitting consists of estimating the time trend of population numbers-at-age most consistent with available information. These models are very flexible in their use of survey data. All data, including fishery age and length composition, are considered to have sampling variability associated with them. Moreover, survey data can be used in a way that corresponds more closely to how the data were collected. For example, the assessment model can be fit to the biomass trend and age composition separately, rather than to a derived set of indices of abundance-at-age. Surveys can be regarded as either an index of abundance or an absolute abundance estimate. Although assessment results are more precise when it is possible to assume that the survey is an absolute estimate, the assessment will be biased if this assumption is incorrect.

Residual analysis may provide some clues to the potential magnitude of vessel avoidance effects for both VPA and statistical assessment models. A consistent pattern in the residuals for a survey is evidence of either a change in the survey or a change in the stock (e.g., a shift in the distribution of the modelled population). A useful diagnostic is a comparison of the root mean square error (RMSE) of the model fit to a survey with the measurement error of the survey. An RMSE much larger than survey measurement error (the most common situation) can be an indication of unmodeled process error, though determining the source of this error is often difficult. If the survey coefficients of variance are used in the fit, they may be scaled to be commensurate with the RMSE in an iterative tuning process. However, this approach simply accommodates the process error, assigning it as some kind of measurement error, rather than identifying the source of the error and modelling it appropriately.
The influence of errors in the survey due to vessel avoidance depends on whether or not the survey estimate is considered an absolute estimate or an index of abundance. In the case of an absolute estimate, the long-term mean error (bias) between true and estimated biomass will result in long-term biased advice. In both cases, in-between year variability may introduce “year-effects” in the survey estimates due to annual differences in average avoidance effects. When considering the potential contribution of vessel avoidance to year effects, it is important to realize that there are other serious year effects including partial coverage (e.g., annual fluctuations in horizontal and vertical availability), and the usual measurement errors associated with taking a number of observations (samples). The importance of the avoidance error must be considered in comparison to these other sources of error and the overall precision required. Vessel avoidance effects that vary randomly from year to year would lead to increased uncertainty in assessment results, but not necessarily a bias (Shepherd, 1999). Some statistical age-structured models using Bayesian methods (Millar and Mayer 2000) or Kalman filter methods (Fryer et al, 1999 and Gudmundsson, 1994) attempt to estimate the average year effects and provide estimates with appropriate precision. However, there still is a tendency for such models to overfit the final survey value, even though the estimated uncertainty may be more realistic.

Vessel avoidance effects can also introduce trend into an abundance time series - chronically over the life of a vessel, and episodically as vessels are replaced. It is also important to realize that vessel differences are not limited to the sound signature contrast between noise-reduced and non-noise-reduced vessels, as conventionally designed vessels differ widely in many respects, only one of which is radiated noise (e.g. Mitson and Knudsen, 2003). Even where the same vessel is used, the noise signature/emission may change substantially through its life time and may become another source of bias if this alters reactions to the vessel (De Robertis et al., 2008). When the vessel conducting the surveys has changed, differential avoidance should be incorporated into the stock assessment model if continuity in the time series is assumed. This can be addressed through inter-vessel calibration (e.g., Dorn et al., 2008).

Unlike many other survey methods, acoustic surveys typically produce a biomass or numerical estimate that is directly interpretable as measurement of the abundance of
the surveyed population. Consequently, the catchability coefficient \( q \) estimated in the assessment model can be considered as a scalar relating population biomass to survey biomass. The degree to which \( q \) is less than one provides some inference about the potential magnitude of vessel avoidance. Other potential biases in the conversion of backscattered energy to biomass (e.g., target strength), or availability of fish to acoustic methods (e.g., the dead zone), could have a similar effect on catchability. When \( q \sim 1 \), vessel avoidance effects are relatively minor (subject to the caveat that the other components of the biomass estimate are also appropriate).

### 5.6 Methods of Correcting for Vessel Avoidance

Vabø et al. (2002) quantified vessel avoidance of Norwegian spring spawning herring as a function of depth \( d \). Using a weighted mean vessel avoidance coefficient (VAC) at depth \( d \), defined as \( s_{A,\text{pass}}/s_{A,\text{ref}} \), where \( s_{A,\text{pass}} \) is the herring \( s_A \) measured during vessel passage and \( s_{A,\text{ref}} \) is the \( s_A \) averaged over a reference period before the vessel passed during a series of experiments.

Løland et al. (2007) assessed the relative contribution of five important sources of uncertainty, including three acoustic signal correction factors for vessel avoidance, acoustic shadowing and depth-dependent target strength, as well as sampling errors in acoustic and trawl measurements, respectively. The acoustic signal corrections were described by parametric functions with uncertain parameters. The parameter uncertainty was represented by simulated values from the estimated distributions.

Hjellvik et al. (2008) focused on vessel avoidance only, using generalized linear models fit to experimental data to estimate depth-dependent correction factors. One approach corrected each depth layer separately. As this can lead to problems if fish dive between those layers; they also corrected the total abundance based on the mean depth of the herring at the time of vessel passage. The authors drew attention to the variability of the reactions between experiments, and suggested this may be related to the experimental design; specifically, the use of small vessels and surface moored buoys, which potentially can act as fish aggregation devices (FADs) and attract fish underneath them, making the reference density artificially high (see also Røstad et al., 2006). For this reason, bottom-mounted transducers were recommended as the best.
method for this sort of experiment. Other sources of variation might be the recent experience of the fish schools – feeding, or being fished upon (c.f. Chapter 4). It may be impossible for such experiments to be repeated at a scale that makes them representative of the survey.

An example of how measurements of vessel avoidance can be incorporated into stock assessment and fisheries management is the use of the vessel comparison experiments in the Gulf of Alaska between the R/V Miller Freeman (MF) and the noise-reduced R/V Oscar Dyson (OD), which took over surveys for walleye pollock formerly conducted by the R/V Miller Freeman in 2008. Acoustic surveys of pre-spawning aggregations of walleye pollock have been used since 1981 to monitor stock abundance, and to allocate the TAC (total allowable catch) during the winter season among management areas. The survey in Shelikof Strait, where over half of the population spawns, is also used in the assessment model as an index of total abundance. The vessel comparison experiments estimated the OD to MF ratio of pollock abundance for the Shelikof Strait area to be 1.132, while the ratio for the Shumagin area was 1.31 (De Robertis et al., 2010), implying that the biomass in the Shumagin area has historically been underestimated relative to Shelikof Strait. The working hypothesis for the higher ratio in the Shumagin area is that the fish are distributed shallower than in Shelikof Strait, and consequently exhibit a stronger avoidance reaction.
With respect to the stock assessment, several approaches were explored for incorporating the results of the vessel comparison experiment. The simplest approach was to rescale the MF time series using the OD to MF ratio from the vessel comparison experiment so that it was comparable to the OD measurements (because the Shelikof Strait survey is treated as an index of abundance it makes no difference which time series is scaled to the other.)

Alternatively, the MF and the OD time series were treated as independent survey time series, and the vessel comparison results were included in the log likelihood of the assessment model. This likelihood component is given by:

$$
\log L = \frac{1}{2}\left[ \frac{1}{p+\delta_{OD:MF}} - \log(q_{OD}) - \log(q_{MF}) - \delta_{OD:MF} \right]^2
$$

(5.3)

where $\log(q_{OD})$ is the log catchability of the OD, $\log(q_{MF})$ is the log catchability of the MF, $\delta_{OD:MF} = 0.1240$ is the mean of log scale paired difference in backscatter, mean[$\log(s_{AOD})-\log(s_{AMP})$] obtained from the vessel comparison, and $\sigma_S = 0.0244$ is the standard error of the mean.

The impact on assessment results and recommended TACs was relatively modest regardless of the modeling approach. The ending year spawning biomass and projected TACs varied 5-7% across different model configurations, and population biomass varied by about 3%. Comparison of the percent allocation of TAC by management area with and without multipliers indicates that the effect of applying calibration multipliers is to increase the TAC allocation to the Shumagin area by about 5%, primarily at the expense of the Chirikof area (i.e., Shelikof Strait; figure 5.1) with an overall population biomass difference of about 3%. While models that include a likelihood component for the vessel comparison experiment are a better approach from a technical perspective, there would be little consequence to using the simpler approach of rescaling the biomass estimates from one vessel to the other. Some care is warranted with the likelihood component approach if other structural assumptions of the assessment are questionable, such as the assumption that a

5.7 Concluding Remarks

Overall, the quantitative body of work on fish reactions to approaching survey vessels indicates that in some cases, vessel avoidance behaviour can substantially impact acoustic measurements and trawl catches. The strongest effects tend to be observed for organisms distributed near the surface. For all taxa studied, other than Antarctic krill, there appears to be some indication that vessel reaction reduces acoustic abundance estimates recorded by the vessel at the time of passage (Box 5.1). It is also clear that in some, but not all cases, surveys using a noise-reduced vessel will produce higher abundance estimates than those from a vessel that is not noise reduced due to decreased avoidance responses to the noise-reduced vessel. However, the available quantitative estimates of vessel avoidance are highly variable, and it is clear that the current understanding of vessel reaction is not sufficient to predict the impact of vessel reaction on abundance measurements with much certainty (e.g. Hjellvik et al., 2008, Chapter 4). A better understanding of the variability in vessel avoidance between year and season for a particular stock is clearly required. At this early stage, fish avoidance should be estimated for each given situation, or better yet, monitored continuously during a survey. There have been some initial efforts at monitoring vessel avoidance from a survey vessel, e.g. the method used by of Soria et al. (1996), where the school counts as a function of athwarthship distance was measured, or using multibeam sonar to calculate “phantom echogram” as a function of athwarthship distance (Patel and Ona, 2009). However, development of new methods and refinement of these techniques is needed before vessel avoidance to a survey vessel can be monitored routinely. Ultimately, surveys can be designed to minimize the biases produced by vessel avoidance. This may be a reasonable consideration during survey planning if vessel avoidance is thought to be a major source of error, and enough is known about the population to make useful generalizations.

When applying corrections to part or all of a survey it is important to have some estimate of precision of the correction factor. If corrections are made using factors with poor precision derived on too fine a scale, this process can introduce noise in
addition to the corrections for the observed effects. Care needs to be taken to ensure that data are aggregated in a way that reflects the temporal or spatial variability of the effect and the precision of its measurement. For example, rapidly fluctuating effects on a fine scale may be best considered as noise and corrected using an overall mean. In contrast, slowly changing effects or predictable influences dependent on well-known drivers such as light level or tide may be best corrected by aggregating over time of day rather than spatial averages.

When designing surveys it may be useful to anticipate potential vessel-related effects. Maintaining consistency in indices or abundance estimates is an essential part of good survey design. Use of the same vessel for an abundance time series is beneficial as this should result in higher consistency. When multiple vessels are used in an abundance time series, either within or among years, the vessel effect should be taken into account. In a multi-ship survey design, allowing for overlapping coverage will provide the opportunity to evaluate differences due to vessels under survey conditions. When vessels in a survey time series are replaced, vessel comparisons should be conducted to estimate the impacts of the change on the survey.

5.8 Summary
• Vessel reactions have the potential to introduce large biases in acoustic measurements.
• Some surveys appear to be insensitive to these problems having consistent time series with small year effects indicating either only low levels of avoidance or dependable effects giving an acceptable mean over the duration of the survey.
• The use of survey data as an index can reduce the impact of vessel avoidance when used in assessments.
• The importance of vessel avoidance and its influence on assessments needs to be judged relative to other sources of bias and variability.
• To correct a survey for the bias caused by avoidance, there are two strategies: Understand the avoidance reaction to minimize the effect, e.g. by surveying the stock in favourable, non-responding situations. Second, measure the avoidance continuously. These recommendations also apply to the new generation of noise-reduced vessels.
• When changing the vessel that is used to obtain a time series, expect different survey results and design vessel comparisons to correct for this effect.

• Multi-vessel surveys should be designed with some spatial overlap between vessels.
We reviewed the literature and summarized the available quantitative measurements of the effects of vessel passage on acoustic measures of abundance ($A$) compared to the undisturbed state (i.e. $VA = A_{\text{pass}} / A_{\text{ref}}$). Symbols indicate mean ratio of an abundance measurement made during vessel passage to the undisturbed abundance. Each experiment is plotted against the mean depth of the animals in the experiment. 95% confidence intervals for $VA$ are given where available. The number in the figure legend indicates the data source.

**Methods:** When individual replicate measurements were accessible, a rough mean $VA$ was estimated as $\exp[\text{mean}\{\ln(A_{\text{pass}}/A_{\text{ref}})\}]$ where $A$ is the acoustic abundance during vessel passage and a reference period when the fish are presumably undisturbed by the vessel. The 95% confidence intervals for $VA$ were estimated as
\[
\exp[\text{mean} \{\ln(A_{\text{pass}}/A_{\text{ref}})\} \pm CI],
\]
where CI is the parametric 95% confidence interval computed on \(A_{\text{pass}}/A_{\text{ref}}\). The confidence intervals should be taken as rough estimates only, as they do not account for biases such as calibration uncertainty and the data may not be completely independent. Cases which did not lend themselves to this type of analysis are shown without error bars. The depth of the organisms was taken as the mean depth if reported, or the midpoint of the depth range either explicitly reported or estimated from the publication. Some depths are shifted slightly to improve the data presentation.

**Data Sources:**  1 Hjellvik et al., 2008; 2 Skaret et al., 2005; 2006; 3 Fernandes et al., 2000; 4 De Robertis et al., 2010; De Robertis and Wilson 2010; De Robertis and Wilson, 2011; 5 Soria, 1996; Gerlotto et al., 2004; 6 Jørgensen et al., 2004; 7 Brierley et al., 2003.

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**Chapter 6. Towards a Conceptual Model of Fish Avoidance**

Anders Fernø

**6.1 Introduction**

Although physiological limits set an absolute threshold of detection by fish to any stimulus emitted by the vessel and its gear (e.g., Chapter 3), great variation in fish response has been documented (e.g., Chapter 4). In other words, fish are not machines, perception does not equate to reaction, and this simplification must be rejected. It is clear that fish receive acoustic, physical, chemical, biochemical, visual, electro-magnetic, and other sensory input. As with any animal, fish filter information from their sensory systems to obtain an integrated understanding of their immediate environment: “…because the [Darwinian evolutionary] trial-and-error procedure has gone for billions of years, (...) every living thing has or is a machinery for learning, remembering, and forecasting. The objective is to provide anticipatory reactions to the interactions with the external world” (Marchetti, 1998). Measuring fish reaction to a single stimulus is thus not sufficient if we want to have a correct understanding of fish avoidance of fishery research vessels (FRV).
Beyond an accurate description of how fish react, systematic analyses of ultimate (i.e., the functional significance of the reactions) and proximate (i.e., short-term motivational systems) factors provoking that reaction are generally lacking. Literally: What does a vessel actually mean for the fish? Does a fish experience a vessel as food, predator, mate or unknown object; and can this conceptual approach further our understanding and our predictive capacity?

Fish exhibit life history and natural history with an evolved repertoire of behavioral patterns and motivational systems, and their reactions to stimuli reflect these adaptations. The difference between a cod and a herring may be as pronounced as between an antelope and a lion, and nobody would expect the latter pair to behave in a similar way. At the same time, there are basic behavioral similarities among vertebrates (e.g., predator avoidance). Thus, when interpreting the type(s) of vessel avoidance fish exhibit, it is important to simultaneously adopt a simple conceptual model while realizing the complexities of species-specific response.

Behavioural responses can be categorised along a gradient from general responses released by a range of stimuli in a number of different situations, to specific responses released by particular stimuli and in defined situations. An example of a general reaction is arousal: released by a wide range of stimuli and characterised by increased awareness and an increased tendency to react if the releasing stimulus becomes stronger. Specific reactions are, for instance, escape reactions released by objects possessing eye marks (that appear to represent predators; Karplus and Algom, 1981), or aggressive and/or sexual reactions released by species and sex-specific color patterns (Heiligenberg et al., 1972; Rowland, 1982).

A number of motivational systems have been postulated to explain the variation in response towards a given stimulus, including general arousal as an overarching category of motivation to four specific systems: aggression, sex, food and fright (Colgan, 1993), where the activation level of a tendency determines the strength of the response. Tendencies are important representations of the proximate tools fish possess.
to optimise fitness by making adaptive behavioural decisions, for instance based on
reward-evaluating mechanisms in the brain (Spruit et al., 2001).

Superimposed on general variations in the tendency to react to stimulation is the
variation induced by previous experience. It has long been known that fish can rapidly
learn to associate different cues with reward (e.g., Bull, 1928). Fish learn (e.g., Soria
et al. 1993), and in some cases display remarkable cognitive abilities (Brown et al.,
2006). Fish are easily conditioned to diverse stimuli. For instance, cod trained to react
to blinking lights by food reward maintain the response towards the conditioned
stimulus for several months (Nilsson et al., 2008). Herring “attacked” by trawls
displayed increased avoidance reactions to fishery vessels (Pyanov, 1993). During
initial stimulus exposure an elevated response level is sometimes observed (i.e.,
sensitization), but if the stimulus is not accompanied with any reward or punishment
the response eventually weakens (Hinde, 1974). For instance, Schwarz and Geer
(1984) demonstrated herring in net pens habituated to play-back of vessel sounds, and
Vabø et al. (2002) found that repeated exposures to a passing vessel resulted in
waning response by herring.

6.2 Behavioral Bases for Avoidance
Avoidance is sometimes explained by over-stimulation of sensory organs, essentially
a reaction to unpleasant stimuli. Thus extremely loud sounds may provoke avoidance
(see pile driving, Chapter 3), but it is unlikely that the sounds from approaching
vessels typically reach such high levels. The way in which animals categorize objects
may be pre-adapted and tailored to their ecological niche (Rozin and Kalat, 1972).
Fish may also experience the vessel as a novel object without classifying it into a
certain category. The reaction towards a novel object resembles, however, the reaction
towards predators, with fish initially avoiding the object by keeping a respectful
distance, followed by gradual approach and exploration.

The primary motivational system deciding the response to predators and in fact any
novel object is fright (Colgan, 1993) and specifically the escape tendency, which
should be activated both by a known predator and an unknown threat emitting strong
(e.g., sound) stimuli indicating large size. Previous experience of vessels connected to
“attacks” by moving gear should strengthen the tendency to escape. Anti-predator behavior is an obvious candidate for explaining the response to survey vessels. Fish reaction to vessels is generally simpler than towards natural predators (Fréon et al., 1993), with typical behavior patterns including arousal, horizontal escape, panic, and diving reactions (Olsen et al., 1983; Chapter 4).

Because the preferred depth of pelagic fish is generally explained by trade-offs between feeding opportunities, predator avoidance (Clark and Levi, 1988), and the environmental limits of the habitat (Bertrand et al. 2010), it is reasonable to attribute diving in response to an approaching survey vessel as resulting from an increased perception of predation risk, as the level of satiation and the feeding opportunities have not been changed. An approaching survey vessel has many general features in common with an approaching predator, emitting sound, particle motion and visual stimuli with an increase in stimulus strength over time corresponding to a directed "attack." It can be argued that such a vessel does not constitute an actual threat, but fish often apply a precautionary principle to avoid predation (Lima and Dill, 1990; see also Chapter 4).

There is some evidence that fish under intense predation pressure will evolve rather quickly (Reznick et al., 1997; Walsh and Reznick, 2008), and this may have implications for classifying fish reaction to fishing vessels (Reznick and Ghalambor, 2005). For instance, sea-ranched sea trout reared in tanks for five generations during the freshwater stage respond more often with freezing and less often with escape when attacked by a predator model than wild fish tested in an identical way (Fernø and Järvi, 1998). However, there has hardly been any long-term consistent selection pressure to develop specific reactions to vessels, taking into account the variation in fishing pressure and fishing practices over time. In some instances fish may be able to decrease the risk of capture by escaping from a vessel, while for others it may be fatal to react by downwards swimming if the fish then come into the path of a bottom trawl (Aglen, 1996). The timescale of evolutionary adaptation is much longer than the accelerating pace of human invention, thus specifically adapted responses to fishing vessels may be nascent, at best. Finally, although both fishery research
vessels and predators produce both visual and pressure stimuli, the sound generated by a vessel is orders of magnitude above that produced by a predator.

A fish that responds may have a better chance to escape an oncoming vessel, but avoidance has associated costs. For instance, if the metabolism of a fish is restricted (e.g., low temperatures), reduced metabolic scope after strong reactions could constrain further movement. There is also an opportunity cost, as escaping fish cannot simultaneously perform other activities (e.g., feeding). Competing stimuli, including feeding, may restrict avoidance response by decreasing the scope of activity (Radakov, 1973; Misund, 1990; Kvamme et al., 2003); for instance, the weak avoidance observed in satiated mackerel (Neproshin, 1979). Finally, vessel avoidance may make fish easier to detect by predators and/or escaping fish may be less vigilant to other proximate sources of risk. A balance between the costs and benefits of escape should theoretically lead to an optimal escape distance where the costs of fleeing and remaining are the same (Ydenberg and Dill, 1986; figure 6.1). This “Economic Hypothesis” thus predicts that reaction does not equal perception.

Both external and internal factors should influence the optimal escape distance. A larger and hence a presumably more dangerous predator should provoke escape at a longer distance. The distance is also state-dependent. For example, osmotically
stressed salmon smolts use more of the available scope of activity when reacting to oncoming predators than do smolts adapted to seawater, and thus respond accordingly later (Handeland et al., 1996). For a given predator, escaping at long distances allows fish more time to respond and lower escape speed is thus needed to avoid contact. In a study on vessel avoidance of jack mackerel, Goncharov et al. (1989) found such a graded response, with swimming speed gradually increasing with decreasing distance to the vessel (figure 6.2).

![Figure 6.2 Swimming speed of jack mackerel as a function of distance from the vessel and location. Note that although there are locational differences, the functional form of the distance relationship is constant. Values are represented by ● (left curve), + (middle curve), ▲ (right curve), depending on the logarithmic regression for corresponding areas (from Goncharov et al., 1989).]

### 6.3 Anti-predator Behavior is Species-Specific
The behavioral repertoire of a species has evolved in concert with its anatomical and physiological adaptations. It is ultimately shaped by environmentally determined costs
and benefits resulting in a restricted reaction domain with a limited number of behavioral options. Different stimuli and states may modify anti-predator behavior, but not outside a given range. An overall framework within which to understand the behavior of a species may thus be its life history, which broadly relates proximate decisions (i.e., behavior) to ultimate consequences (i.e., survival and reproduction). Depending on life strategy, and particularly life length, age at first reproduction, and fecundity, species may display risk prone or risk averse decision-making in short-term (e.g., predator-prey interactions) situations.

Figure 6.3 Relative strength of avoidance response across four species, adapted from Olsen et al. (1983).

Figure 6.3 indicates the strength of the avoidance reactions in four different species based on Olsen et al. (1983). Even given different study situations, some interesting patterns can be observed. Of these four species, herring show the strongest avoidance. Herring can live to 15-20 years old, over which time they migrate extensive distances between feeding, overwintering and spawning areas, encountering a diversity of predator types (Fernø et al., 1998). Herring can rapidly swim both horizontally and vertically, and schools have a wide repertoire of avoidance maneuvers when attacked (Pitcher et al., 1996; Nøttestad et al., 2002). Of special interest here is the diving response towards deeper waters when threatened (Nøttestad et al., 2004).
By contrast, capelin show weak avoidance reactions to vessels (figure 6.3; see also Jørgensen et al., 2004). A relatively short-lived species, capelin should be relatively risk-prone. As capelin inhabit colder water, reduced metabolism as a consequence of low temperatures may also set restrictions on activity. Capelin have been observed to migrate to low temperature refuges to avoid predation from cod (Rose and Leggett, 1990). The available evidence thus suggests that capelin primarily avoid predators via habitat selection over active short-term responses to predators. The weak avoidance of survey vessels fits into this picture.

The response strength of cod towards vessels seems to be in-between herring and capelin (figure 6.3). In accordance, the life span of cod is intermediate. The risk of predation decreases over a certain size (Pállsen, 1994), which could result in dampened escape behavior of larger cod (Fernø et al., unpublished observations). Cod seem to show both active and passive responses towards experienced threats with responses ranging from freezing to escape. Polar cod seem to show stronger vessel avoidance than cod (Figure 4.3), although the life span is similar.

The increasing awareness of the existence of different coping styles in individual fish (Øverli et al., 2004) should be kept in mind when trying to understand variation in predator, or vessel, avoidance. For instance, Engås et al. (1998) reported a large variation in response to approaching vessels between and within individual cod. Individual variation is presumably related to state differences and suggests that relatively minor differences in the motivational state can have a strong effect on behavioral decisions.

### 6.4 Developing a General Model

The response of fish to an approaching vessel is an intricate interplay between the temporal increase of the stimulus level, the escape distance, and swimming speed during escape. Processes like habituation, sensitization and muscular fatigue could also influence the response. Internal and external state factors are also critical (figure 6.4).
Although quantitative consideration of all possible factors is not practicable, it is instructive to construct a conceptual model to help place the range of observed responses within a larger context, and one specifically relevant to predator-prey interaction. The simple model below could serve as example of such an approach. A graded response (sensu Olsen et al., 1983) modulated by the ontogenetic, nutritional and reproductive state of the species may be appropriate, although alternate functional forms (e.g., nonlinear, threshold; see Chapter 4) are also possible.

Reaction, whether avoidance or attraction, must start with perception, a complex physiological response (see Chapter 3) mediated through internal state (e.g., short-term motivational state, experience) and external state (e.g., environmental conditions, social interactions; figure 6.4). In general, the *stimulus level* at the sensory receptors of a fish can be described by some functional form of sound pressure, Doppler effect, particle displacement, as well as non-auditory (e.g., visual) stimuli. The *reactivity level* of a fish in an avoidance situation can then be defined as risk willingness based on an evaluation of relevant internal and external parameters including but not limited to: condition index, maturity stage, and satiation; as well as predator presence and prey availability. The observed *reaction* is therefore a function of both the stimulus level filtered through the reactivity level, and the specific reaction pattern of the species in question.
In addition to this simple model, additional factors may be important in determining or regulating vessel avoidance:

- **Ambient Noise Level** in the sea influences the hearing threshold through masking and thereby the reaction distance towards vessels (see also Chapters 2 and 3).
- **Temperature** in the sea could influence escape speed.
- **Fish size** should influence vessel avoidance as size is correlated with risk of detection, swimming speed and the relationship between present and future reproduction. For instance, the different response of large and small cod to seismic shooting (Engås et al., 1993) could indicate a size-dependent reaction threshold.
- Although **School size** should influence avoidance as large group size increases individual safety and thereby decreases reaction to predators (Magurran et al., 1995), the few observations on vessel avoidance do not support this hypothesis.
- **School Density** could influence the dynamics of moving masses, with the transfer of the reaction through waves of agitation (Gerlotto et al., 2006) facilitated by short inter-fish distance. The inter-fish distance could also influence the outcome of the collective dynamics mediated by self-organization (Viscido et al., 2004) taking place after schooling fish have reacted to a vessel. High-density schools may already be in a state of general arousal specifically relative to predator defense (Nøttestad et al., 1996) and thus be expected to show stronger avoidance. The response can also depend on the reaction of other fish.
- **Aggregation Pattern** and occurrence of other schools near-by could influence reaction intensity as the presence of other schools may decrease fright reactions. On the other hand, experienced fish can transfer a conditioned avoidance reaction to naïve fish (Soria et al., 1993). Fish swimming deep can, for instance, react to a passing vessel because they come into contact with fish escaping from more shallow waters – the “cascade effect” (Gerlotto et al., 2006).
- **Time of Day**, or diel variation in avoidance reactions can have two causes. First, vertical migrations can influence the distance between the fish and the vessel. For instance, herring swimming closer to the surface at night show stronger avoidance reactions (Vabø et al., 2002). Second, the responsiveness to a given stimulus could vary throughout the diel cycle. For instance, herring show particularly strong avoidance to vessels at dusk after ascending towards the surface, indicating that
there are subtler diel variations perhaps related to the risk of predation (i.e., during the crepuscular period; Vabø et al., 2002).

- **Risk of Predation** may increase the reaction to a vessel as multiple predators enhance total risk and thus prey response (Sih et al., 1998). However, the presence of multiple predators could also force the fish to more balanced reactions, and it has been suggested that the weak vessel avoidance observed in pelagic fish under high predatory pressure from seals reflects a low estimated relative risk increase imposed by the vessel (Misund, pers. com.).

- **Experience** of vessels may enhance, or dampen, response. Fish passed over by vessels without any consequences may habituate to the stimulus and stop reacting. This could be the case in areas with heavy boat traffic such as the North Sea, although fish in this area relatively often experience vessel sound in combination with fishing gear (Özbilgin and Glass, 2004) that should counteract habituation. It would be interesting to see if there is a correlation between boat traffic and vessel avoidance in different areas.

6.5 **Concluding Remarks**

Fish avoidance of vessels has so far not been adequately analysed based on a behavioral context, and specifically within the context of response to predators. Without a systematic approach taking into account species differences and state variations, accounting for the variation in avoidance may be impossible. Models combining internal and external factors could represent a development from models only including external factors (Olsen, 1983), depth-dependent pragmatic models (Vabø et al., 2002) and models including reaction threshold and external factors (Handegard and Ona, 2001). There is a need for a shift from descriptive studies to studies on the functional significance of the observed behavior permitting mechanistic understanding and increased predictability relative to survey design and ultimate (e.g., population assessment) outcomes. With some notable exceptions (Misund, 1990; Misund and Aglen, 1992; Volpatto et al., 2002), proposed models on fish avoidance have not been rigorously tested. The available evidence suggests that avoidance of survey vessels may functionally represent antipredator behavior, and conceptual analyses based on the economic hypothesis of the response to predators (Ydenberg and Dill, 1986) indicate that the balance between costs and benefits of antipredator
behavior determines the response; although more studies on the sound characteristics critical for eliciting avoidance are needed. It may be possible to accurately model avoidance purely based on information on the internal state of the fish and the external situation (i.e., dominant parameters), with an increased understanding of the attributes of the sound signal that elicit avoidance responses within the larger environmental and ecological contexts. A general model should be tuned for different species by iterative optimization, modulated by in situ sensor input and actual experiments (see also Chapters 4 and 7) focused on identifying important forcing factors (e.g., day versus night, seasonal shifts, and/or vessel type). Although many factors may influence vessel avoidance with the outcome determined by the “global situation” (Gerlotto et al., 2006), in the end only a restricted number of the most crucial factors should be included in the model, otherwise the complexity becomes difficult to handle. A first step is to try to put the many contrasting observations on vessel avoidance into a simple common framework, make predictions based on this framework and test these predictions on different species in different situations.

6.6 Summary

- Avoidance is a reaction to “unpleasant” stimuli.

- Anti-predator behavior is an obvious candidate for explaining the response to a survey vessel.

- Reaction does not equal perception.

- Anti-predator behavior is species specific.

- Development of a general behavioral model should be based on both internal and external factors including: ambient noise level; physical characteristics of the sea; school size and density; aggregation patterns; time of the day and season; risks of predation; and experience.
Chapter 7. Designing experiments to evaluate fish reactions

F. Gerlotto and E. Josse

7.1 Introduction
Experiments measuring the main components of fish behaviour with respect to schooling and avoidance have been performed for decades. Two milestones can be identified. Radakov (1973) defined specific patterns of fish school avoidance manoeuvres based on laboratory observations. Olsen (1969a, 1969b; Olsen et al., 1983a, 1983b) designed in situ experiments involving an instrumented buoy for observation of fish reactions from the side of the research vessel. These laboratory and field results set the stage for a great variety of observations and experiments documenting the occurrence and type of fish avoidance of vessels. Since the 1990s, the invention/use of new instruments has allowed much better observation and recording of fish behavioural dynamics, including digital echo sounders and their related software (Axenrot et al., 2004), multibeam sonar (Reid, 2000), acoustic tags (Engås et al., 1998; Winger 2004), and acoustic cameras (Josse et al., 1998).

Considering the characteristics of sound, fish hearing and behaviour detailed in the former chapters, it is not surprising that no single experiment can give universal results. Results have been extremely diverse, with the proportion of observed fish avoiding the vessel ranging from none (Fernandes et al., 2000a; Gerlotto et al., 2004) to more than 80% (Soria et al., 1996). For instance, measurements of avoidance of Clupeids in several areas using research vessels confirmed that fish reaction to vessel noise is not a simple linear process between reaction and stimulus. Although some pattern can be observed across geographic areas as disparate as the Mediterranean and the tropical Atlantic Ocean (Soria et al., 1996; Gerlotto et al., 2004), the degree of response in one place and time seems very difficult to predict based on results collected from elsewhere.

After more than four decades and a large number of observations and experiments, and despite the fact that the major result is the confirmation of a high variability in the
responses, a few patterns have been extracted (see also Fréon and Misund, 1999 for a synthesis).

**Horizontal avoidance.** Appearing at large (Neproshin, 1979; Goncharov et al, 1989; Diner and Massé, 1987) or short distances from the ship (Misund, 1990; Brehmer, 2004); some complex patterns of horizontal avoidance have been modelled in relation to vessel noise (Soria et al., 1993) which imply that fish are able to evaluate sound gradients and move towards less noisy areas (fig. 7.1).

![Figure 7.1. Comparison of avoidance reactions of schools to a research vessel in the Mediterranean, in West Africa (Senegal and Ivory Coast) and in South America (Chile). Histograms show the number of schools observed on the side of the ship with multibeam sonar. Three different research vessels were involved: R/V Garcia del Cid in the Mediterranean, R/V Antea in the Atlantic Ocean, R/V Abate Molina in Chile. In the case of the Mediterranean we could conclude that 76 % of the schools avoided the vessel path (from Soria et al., 1996; Gerlotto et al., 2004; Brehmer, 2004).](image)

**Vertical avoidance.** Always performed when schools occur at shallow depths (Gerlotto and Freon, 1992; Gerlotto et al, 2004), fish also perform vertical avoidance at larger depths depending on the species (Olsen et al, 1983; Wilson, 2003).

**Effect of the environment.** The same species in the same place can display different avoidance behaviours depending on its environment, e.g. diel period or meteorological events (Gerlotto et al, 1997); the same species in different places
shows different avoidance patterns due to differences in the fishing pressure (Brehmer et al, 2000).

**Existence of attraction.** For some species, particularly tunas (e.g., Dagorn et al., 2001), vessels can be strongly attractive. La Pérouse related in 1786 that a tuna marked by scars due to unsuccessful harpooning followed his frigate from Tahiti to Hawaii. More generally, attraction to FADs has been observed for many species (Røstad et al, 2006), including small pelagics, *e.g.*, in the Java Sea (Potier et al., 1997).

**7.2 Experimental approaches to measuring fish avoidance**

To accurately document fish avoidance, three different types of measurements must be collected: those of the stimulus, those characterizing the environment, and the reaction of the fish. Both *in situ* observations and tank experiments can be used to evaluate avoidance. Once several sets of observations/experiments have been completed within and among geographic locations, we might be able to define some general patterns of vessel avoidance, and specifically to sound stimuli. Following the literature (see Appendix 7.1), we categorize avoidance experiments into principal types.

**7.2.1 Opportunistic acoustic observations**

This kind of observation is the easiest to perform, is routinely collected in acoustic surveys, and can give valuable information on avoidance. When large-scale comparisons are made, “universal” patterns of response, and/or internal and environmental factors impeding or enhancing response, may be discernable. Although not explicitly experimental, such data do provide a crucial first step as assessing likely important factors in avoidance, and thus to experimental design. Currently restricted to data collected by survey and research platforms, there is no reason that opportunistic acoustic data could not also be collected by fishing vessels, greatly expanding the available data. For instance, Table 1 is an example of such a comparative analysis on the Clupeid *Sardinella aurita*. 

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Table 7.1. Example of comparative analysis of avoidance reactions of Clupeid schools in different areas and under different conditions. In Venezuela, Senegal and Ivory Coast fish were *Sardinella aurita*. In the Mediterranean it was a mixture of anchovies and Clupeids (from Brehmer et al., 2000).

<table>
<thead>
<tr>
<th>Factor</th>
<th>Horizontal Avoidance (% response)</th>
<th>Source</th>
<th>Vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global effect</td>
<td>64% schools avoiding</td>
<td>Adriatic sea (1994-1995)</td>
<td>R/V Garcia del Cid</td>
</tr>
<tr>
<td></td>
<td>28% schools avoiding</td>
<td>Catalan sea (1994-1995)</td>
<td>R/V Garcia del Cid</td>
</tr>
<tr>
<td></td>
<td>34% schools avoiding</td>
<td>Venezuela (1998)</td>
<td>R/V Antea</td>
</tr>
<tr>
<td></td>
<td>79% schools avoiding</td>
<td>Ivory Coast (1998, day)</td>
<td>R/V Antea</td>
</tr>
<tr>
<td></td>
<td>93% schools avoiding</td>
<td>Senegal (1999, day, trawling)</td>
<td>R/V Antea</td>
</tr>
<tr>
<td>Bathymetry</td>
<td>61% more avoidance in shallower waters</td>
<td>Adriatic vs. Catalan sea (1994-1995)</td>
<td>R/V Garcia del Cid</td>
</tr>
<tr>
<td>Areas</td>
<td>45% more avoidance in Ivory Coast than in Venezuela</td>
<td>Venezuela (1998) vs. Ivory Coast (1998)</td>
<td>R/V Antea</td>
</tr>
<tr>
<td>Period (day/night)</td>
<td>21% more schools avoiding by day</td>
<td>Venezuela (1998)</td>
<td>R/V Antea</td>
</tr>
<tr>
<td>Vessel speed</td>
<td>21% more schools avoiding at low speed</td>
<td>Venezuela (1998)</td>
<td>R/V Antea</td>
</tr>
<tr>
<td>Fish length</td>
<td>16% more juvenile fish schools avoiding (compared to adults)</td>
<td>Venezuela (1998)</td>
<td>R/V Antea</td>
</tr>
</tbody>
</table>

### 7.2.2 Single vessel experiments

Several acoustic methods of observation have been used. *Low frequency sonar* (12 to 70 kHz), either *single beam* (SBS) or *omnidirectional multibeam* (OMS), have been especially useful for measuring the reaction of fish schools in front of the ship. SBS results have been presented since the 1970s (*e.g.*, Neproshin, 1979), but acoustic analysis dramatically increased with the use of OMS (*e.g.*, Bodolt and Olsen, 1977; Cushing, 1977; Diner and Massé, 1987; Misund, 1990); and some surveys (*e.g.*, Diner...
and Massé, 1987; Misund, 1990) were specifically designed to address fish avoidance of vessels.

High frequency multibeam sonar (MBS, 200 to 455 kHz) appeared in the late 1990s (Gerlotto et al., 1999; Reid, 2000). Two major uses of MBS are developed for avoidance measurements: first, an evaluation in real time of the avoidance reaction, when deploying the MBS in a vertical plane perpendicular to the route of the vessel (fig. 7.2.). In this case the schools of fish are observed at any distance from the ship, and the difference between the theoretical distribution for no avoidance and the actual one allows an estimation of the avoidance reaction (Soria et al., 1996).

Figure 7.2: Evaluation of school avoidance using MBS. Above: frequency histogram of the lateral distances between the centres of gravity of the schools and the vessel. Dashed line is the average number of fish to be expected at any distance from the vessel in case of no avoidance. Below: projection in a vertical scale perpendicular to the vessel path of all the schools (more than 1200) detected during a survey. A1 simulates the half area insonified by a single beam echo sounder. The rectangle A2, delimited horizontally by the surface and the depth 55m, and vertically by the vertical
lines at 0 and 70 m to the vessel, represents the measurement area where no bias due to attenuation is expected. From Soria et al., 1996.

The second use is to evaluate the detailed reaction of schools, observing their changes in location (vertical avoidance, cf Gerlotto et al., 2004) or in shape (e.g., Soria et al., 1996; fig. 7.3).

Figure 7.3. Schematic diagram of the “double wave of avoidance” mechanism. Time 0: schools at distance to the vessel above the reaction threshold. Time 1: school at medium distance, first wave of avoidance. Time 2: schools below the vessel, second wave of avoidance. White dots: schools avoiding during the first wave, grey dots: schools avoiding during the second wave; black dots: schools actually recorded by the echo sounder. Black arrows: propagation of sound in the axes of highest intensity. Grey arrows: movements of schools. The “butterfly effect” of the noise propagation is described by the solid line around the vessel (see Chapter 2). From Soria et al., 1996.

Split-beam tracking is a very simple and potentially useful method to evaluate avoidance. Most scientific, and even professional, echo sounders are split-beam such that fish movements (e.g., diving, systematic movement away from the vessel) can be observed (fig. 7.4). Moreover, one of the biases that can be induced by avoidance, i.e. change in tilt angle of the fish, can be measured in a routine way and used for correcting the abundance estimates at each point of the survey (e.g., Axenrot et al., 2004).
Figure 7.4. Example of 3D movements of single fish using split-beam sonar. This example displays vertical movements of tuna in the Indian Ocean, from 20 to 70 m depth. Three types of information are displayed: horizontal movement inside the beam (circle, upper left), vertical movement (echogram at right), and the TS histogram, which includes information on fish tilt angle. From Josse, pers. comm.

7.2.3 Multiple simultaneous vessel experiments
An extensive description of the experiments comparing data from multiple vessel experiments is given in Chapter 4. Besides the obvious advantage in experimental design, multiple vessels allow for intercalibration, as would be needed if a newer vessel were replacing an older one.

7.2.4 Autonomous Underwater Vehicles (AUV)
Assuming that an AUV does not induce any reaction of the school comparable to that induced by a survey vessel, comparing the results from an AUV to a vessel allows the measurement of avoidance reactions. Patel et al. (2004) used an AUV to observe a large layer of wintering herring in Norway, and found that at small distances the AUV did produce some reaction. Scalabrin et al. (2009) showed that using an AUV in the deep zone with multibeam sonar oriented toward the surface could provide important results on the actual 3D and dynamic reaction of the fish to the ship. Fernandes et al.
(2000a,b) used an AUV specifically to document negligible reaction of herring to a noise-reduced vessel (*R/V Scotia*).

### 7.2.5 Floating (buoys) or fixed platforms

First used by Olsen *et al.*, (1983a, 1983b) to document the reaction of fish to an approaching vessel, an autonomous echo sounder attached to a floating or fixed buoy can record the distribution of the school as a research vessel passes a few meters from the buoy (fig. 7.5). The changes in the fish distribution observed below the buoy will give an indication of the vertical (location of targets) and lateral (decrease in density) avoidance effect of the vessel (fig. 7.6).

![Figure 7.5. Drawing of the floating buoy designed by Olsen et al. (1983) for measuring the avoidance. This system has been adapted by numerous authors: for instance the Bergen Acoustic Buoy consists in a transducer rig and an instrument pod instead, including a Simrad EK60 echosounder (replacing the old echosounder SIMRAD EYM and tape recorder used by Olsen et al aboard the assisting boat), plus a PC, various communication instruments, GPS and a battery package.](image-url)

Figure 7.5. Drawing of the floating buoy designed by Olsen et al. (1983) for measuring the avoidance. This system has been adapted by numerous authors: for instance the Bergen Acoustic Buoy consists in a transducer rig and an instrument pod instead, including a Simrad EK60 echosounder (replacing the old echosounder SIMRAD EYM and tape recorder used by Olsen et al aboard the assisting boat), plus a PC, various communication instruments, GPS and a battery package.
Figure 7.6. Example of results obtained with a drifting buoy. Above: echogram from the buoy’s echosounder showing the reaction of a herring layer. Time is negative before the passage of the ship over the buoy (at time = 0) and positive after the passage. Below: variations of echo energy. The reactions begins at 1200 m from the vessel (from Mitson and Knudsen 2003).

This approach has been applied with some variation, mostly with the use of FADs, where the attractive effect of the buoy is explicitly acknowledged. Taking advantage of the attractive effect of FADs allows observation on schools that are concentrated below the FADs, whereas autonomous buoys are more adapted to observation of fish layers. Some experiments performed with a small dinghy instead of a completely passive buoy (e.g., Gerlotto and Fréon, 1992) made it possible to locate the buoy over schools. Røstad et al., (2006) examined fish attraction to a merchant ship using buoys.

7.2.6 Acoustic tags
Tagging studies have been conducted on a wide diversity of fish. Soria et al. (2009), tagged jack mackerel, *Decapterus punctatus*, at La Reunion Island (Indian Ocean), releasing the fish on an artificial reef surrounded by fixed hydrophones, an experimental set-up allowing calculation of the trajectories of tagged individuals. Engås et al., (1998) and Winger (2004) investigated the reaction distances of acoustically tagged Atlantic cod in response to approaching trawlers. Using an
acoustic positioning system, Voegeli et al., (2001) monitored the behaviour of individual fish for the periods before, during, and after an encounter with a vessel (fig. 7.7). Reaction distances of individual fish were documented as far as 1.5 km away from the advancing vessel depending on the season, water depth, and vessel speed.

Figure 7.7. Schematic of a tagging experiment on cod. Reaction of cod to a trawling vessel without (center: 10 knots) and with (below: 4.5 knots) a trawl set. Recordings of the position and swimming speed of the fish come from acoustic tags. From Voegeli et al., 2001
7.2.7 Visual observations
Visual observation is a remarkable source of information as it is able to show in detail the reactions of individuals and schools. Aerial observation, including LIDAR, minimizes (depending on shadow) or prevents fish response to the observer. For example, the variation in shape and the dynamics of reactions of *Harengula sp.* schools in Martinique (French West Indies) was recorded through aerial photography and related to the stimuli of a small boat crossing over the school (Fréon *et al.*, 1993).

7.2.8 Models and simulations
Many conceptual models have been presented that could potentially speak to the effect(s) of avoidance. Olsen (1983b) presented the pioneering conceptual work. Misund (1990) articulated the potential relationship between the direction of avoidance of schools and the "butterfly" directivity diagram of sound transmitted by a ship. Soria *et al.* (1996) proposed the "double wave of avoidance" explaining the bimodal distribution of schools at the size of a ship (fig. 7.3). Soria *et al.*, (2003) proposed a conceptual model relating the variation of school shape due to vessel-based reaction. In addition, several simulations exploring reaction to predators through individual-based models may also be useful (Vabø and Nøttestad, 1997; Couzin *et al.*, 2002; etc.). See also Chapter 6.

7.3 Constraints on avoidance experiments
The extreme variability of published results on fish avoidance to vessels (see Chapters 3 and 4) suggests that there are many factors in play. Both internal and external state variables must be taken into account when designing avoidance experiments, including but not limited to species-specific physiology, learning and habituation, the observation platform itself, scale as mediated through school size, and the larger environmental and ecological context within which the experiment and the fish reside.

7.3.1 Physiology
Reproductive state is an important determinant of behavioural response in fish (Albaret and Gerlotto, 1976). Hungry fish have different reaction thresholds from satiated ones (Josse *et al.*, 2000; Doray *et al.*, 2008). When conducting behavioural
experiments, these changes in behaviour related to physiology should be known and
taken into account (see also Chapter 3).

### 7.3.2 Learning and habituation

When repeating an experiment on the same group of fish, learning can alter expressed
response (Pyanov, 1993; Soria et al., 1993). Trained fish can display a trend in
reaction to a given stimulus over time. An unknown (noise) stimulus may induce a
higher level of reaction as compared to a familiar stimulus, regardless of the strength
of the signal. Fish schools in an actively fished area may overreact to stimuli from a
fishing vessel as compared to reactions in a non-fished area or to a non-fishing vessel.
*Sardinella aurita* schools in West Africa (where important artisanal and industrial
fisheries exist) showed faster (Soria et al. 1992) and stronger (Brehmer 2004)
avoidance reactions as compared to the same species in Venezuela (where only a
small artisanal fishery is present) when surveyed by the same research trawler *R/V
Antea* (fig. 7.8). Soria et al. (1993) showed that fish knowledgeable about a specific
stress will transmit this information with a resultant increase in the global avoidance
response of the school.

![Figure 7.8](image.png)

Figure 7.8. Comparative values of natural (observed with drifting silent ship) and avoidance (observed on a school chased with the same ship in fishing operation with pelagic trawl) horizontal speeds of *Sardinella aurita* schools observed aboard R/V Antea in Venezuela and Ivory Coast. Blue: avoidance, Venezuela; red: avoidance, Ivory Coast; yellow: natural speed, Venezuela; purple: natural speed, Ivory Coast (From Brehmer, 2004)
A related effect is habituation, if the anthropogenic stimuli do not accompany an additional threat. For instance, Gerlotto et al., (1989) studied the avoidance response of fish schools to artificial and predator-generated sound below an oil extraction platform off Nigeria. The objective of the experiment was to evaluate whether sound transmission could repel fish concentrated below the platform. Figure 7.9 shows the variation of relative values of fish density below (circle) and around (rectangles) the platform while an artificial monotonic sound (250 Hz) was transmitted over the course of 24 hours. A clear pattern of avoidance was observed, albeit at different speeds: very fast at the beginning, then much more stable, especially below the platform.

Figure 7.9. Effect of an artificial sound (250 Hz) transmitted below an oil extraction platform on the density distribution during a 24 hour cycle. * Location of the source (transmission beginning at 11:00 am). Density in relative units, from 0 to >6000. The first image shows the fish distribution before transmission at 9:00 am and the followings display changes in distribution at the beginning of the transmission (2nd image, 11:00 am), 3.5 and 24 hours after the beginning (3rd and 4th images). (from Gerlotto et al., 1987)

7.3.3 Observation platform
In many cases the observation platform is the same as the source of the stimuli (e.g., a research vessel), making it difficult to evaluate the effect of a particular stimulus, as many others are simultaneously emitted by the vessel, and any/all can affect fish behaviour. For instance, one obvious additional source of fish reaction to vessels is
light. Fish are extremely sensitive to light and can display strong avoidance – or attraction - reactions. If no measurement of light levels during the experiment by night are done, it may be impossible to discriminate between reactions due to light versus those due to noise. An example is given by Lévénez et al. (1990) who measured fish abundance in the vicinity of a research vessel while switching a 500 W light on the fore part of the research vessel on and off every five minutes during the night (fig. 7.10).

Figure 7.10. Distribution of fish echoes during the night as observed on the echogram (depth range 50 m), with light aboard the ship alternately on (+) and off (-) in 5 minute periods. From Lévénez et al., 1990

7.3.4 Scale
An important source of changes in fish behaviour is the number of individuals in the group, or school size. This is especially critical when working on pelagic fish in laboratory experiments, where extrapolating the reactions of a few fish to the whole population may be problematic. Radakov (1973) suggested that "an investigation of schooling behaviour demands that we study not only the interrelations of two or a few specimens, but the general regularities inherent to a fairly large school as a unit, in which quantity goes over the quality." At larger school sizes, individuals may no longer be able to sense threats directly, and will instead rely on indirect assessment, namely information transfer.

A related effect is the scale of the observation/experimental set-up. Fish in cages or in tanks, even though the tanks are of large dimension, display different reactions than fish in the open sea. Thus, the perturbation produced by physical limitation of the setting can be stronger than the stimulus under study.
7.3.5 Environmental context
A behavioural reaction is often the result of a synthetic analysis of the different stimuli received, set within the environmental context, or external state. Thus, it is likely that the same intensity of sound will produce different reactions when received by day or by night, in clear or turbid water, etc. (Fréon and Misund, 1999). For instance, Josse (pers. obs.) found that in the Bay of Douarnenez (Brittany, France) the intensity of avoidance reactions to the research vessel varied over the day. Weakest responses were observed at midday. Noise from other sources may also mask school perception. For instance, Gerlotto et al. (1997) showed that fish reactions were completely different before and during the passage of a storm, where the most likely effect was an increase in the background noise level and masking.

7.4 General recommendations.
If the major objective is to evaluate whether and how fish are reacting to a research vessel, it is necessary to measure fish reaction, understand fish physiology and in particular hearing, characterize the local environment, and characterize the suite of stimuli the vessel emits. In most of the cases the measurement is done through the observation of differences in spatial distribution (vertical or horizontal) before, during, and after the passage of the ship.

Experiments designed to understand the behavioural patterns of avoidance have to take into consideration the various specifications of stimuli, as well as the physiological characteristics of fish hearing. So far this has not been the case and almost all the experiments have been simple observation of fish reactions. Identifying which elements of the sound signature, or other vessel-produced stimuli, result in fish avoidance, both within and among systems, in crucial (see Chapter 2). The principal stimuli to take into account include: directivity, tonality, frequency, particle motion, gradients, non-sound stimuli, and ambient noise. Defining the hearing characteristics of the targeted species is also essential (see Chapter 3), e.g., some species are capable of hearing ultrasound. Laboratory experiments in tanks have been performed mostly to measure fundamental behavioural and/or physiological responses, and these are probably the only experimental conditions allowing an analysis of each stimulus
separately, as comprehensive measure of, and control over, the same is virtually impossible in the field. We recommend development of this area of laboratory investigation in order to help define new hypotheses, as well as to develop iterative laboratory and field experiments to test them.

Identifying the type(s) of avoidance response as a function of the particular environmental and ecological conditions under which responses occur requires closer attention, and may be understandable within a larger conceptual (e.g., predator-prey) framework (see Chapter 6). The major factors inducing changes in the behavioural response include learning and habituation, biological cycles, species interactions, density and abundance, etc.

It is and will remain unlikely that the totality of conditions affecting individual fish/school behaviour can be precisely measured (e.g., external conditions such as the presence of predators, and internal state, including previous experiences of the fish, physiological condition, etc., see also Chapter 6). Because of the inherent variability of external and internal conditions, local measurements of fish avoidance are needed even if fish apply "standard strategies" for avoiding vessels.

Finally, a statistics-based approach is indispensable if we are to understand underlying drivers of fish reaction to survey vessels. Clearly, defining the objectives of the experiment and designing accordingly is essential. Thus, experiments designed to address differences in fish reaction may be more fine-grained than those designed to address differences in estimating fish abundance (see Chapter 5). Even given new technologies, it remains extremely difficult (e.g., pressure waves) to impossible (e.g., behavioural conditions) to accurately monitor all sources of stimuli in situ.

Only after repeating an experiment a number of times in a number of areas and under a number of conditions can we expect to extract some pattern from the variability of fish reactions. Although existing experiments have been superficially similar (e.g., use of floating buoys), direct comparison of results is problematic due to differing environmental, ecological, and experimental conditions. To date, comparative studies between conventional and noise-reduced vessels are still too contradictory and not numerous enough to draw significant conclusions as to the effect of vessel noise
reduction on fish avoidance (see Chapter 4). A systematic attempt to create standard experimental conditions, in addition to much more comprehensive measurements across systems and species, could be an objective of a future study group within ICES WGFAST.

7.5 Summary
Field observations reveal "standard" avoidance patterns including vertical and horizontal avoidance, as well as factors affecting the strength of avoidance response, including the effect of the environment and the possibility of attraction to the vessel or measurement platform (i.e., a FAD).

Eight experimental approaches have been developed to examine fish avoidance: opportunistic observations during routine acoustic surveys, measurement of avoidance by a single vessel, comparative multiple vessel observations, use of an AUV, use of floating or fixed platforms (e.g., buoys), acoustic tags, visual observations, and models/simulations.

Five factors should be taken into consideration when designing and/or interpreting avoidance studies: species-specific physiology, learning and habituation, the observation platform itself, scale as mediated through school size, and the larger environmental and ecological context within which the experiment and the fish reside.

Recommendations are given for performing new experiments: define clearly the objectives, design of adapted experiments (depending on the stimuli), standardization of the experiments, selection of methods according to the objectives.

Appendices are provided categorizing experimental methods (7.1) and listing major literature on fish avoidance (7.2).
Appendix 7.1. Synthesis of the main experimental methods, their objectives and limitations OMS: omnidirectional low frequency sonar; MBS: high frequency short range sonar; VES: vertical echo sounder; AUV: autonomous underwater vehicle; + : parameter observed and measured.

<table>
<thead>
<tr>
<th>Measurement method</th>
<th>School movement</th>
<th>School shape</th>
<th>Density changes</th>
<th>TS changes (diving)</th>
<th>Vessel noise signature</th>
<th>Lateral avoidance</th>
<th>Vertical avoidance</th>
<th>Behavioural observation</th>
<th>Other stimuli observed</th>
<th>Observation conditions</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-situ experiment</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>Any, selected</td>
<td>Depends on natural conditions</td>
<td>Mostly on schools</td>
<td></td>
</tr>
<tr>
<td>OMS</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td></td>
<td>Engine on/off</td>
<td>Large distances</td>
<td>On schools, “black box” uneasy to calibrate</td>
<td></td>
</tr>
<tr>
<td>MBS</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td>predation</td>
<td>Short distances</td>
<td>relative values on schools; calibration</td>
<td></td>
</tr>
<tr>
<td>VES</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Light, day/night</td>
<td>vertical</td>
<td></td>
</tr>
<tr>
<td>AUV</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td>Inaccessible areas</td>
<td>Any place (including non navigable)</td>
<td>AUV assumed to have no effect</td>
<td></td>
</tr>
<tr>
<td>Buoy</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td>Plankton, vertical migrations</td>
<td>On layers, difficult for schools</td>
<td>Single point observation. Buoy assumed to have no effect</td>
<td></td>
</tr>
<tr>
<td>Inter-ship</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Not in patchy areas</td>
<td>Costly, sensitive to patchiness, needs statistics</td>
<td></td>
</tr>
<tr>
<td>visual</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>Any stimulus, especially light</td>
<td>Very short distances, experiments</td>
<td>Need to measure the impact of the observer</td>
<td></td>
</tr>
<tr>
<td>Acoustical tagging</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td></td>
<td>Physiology, local environment</td>
<td>On large fish single individual, no knowledge of social effect</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Controlled medium</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td></td>
<td>Any case but non natural conditions</td>
<td>For small fish and particular conditions</td>
<td>Does not show the natural behaviour</td>
<td></td>
</tr>
<tr>
<td>Statistical analysis</td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fishery, traffic, day/night, etc.</td>
<td>No experiment possible</td>
<td>No relationships with actual stimuli</td>
<td></td>
</tr>
<tr>
<td>Multiple stimuli</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td>Particular experiment or controlled areas</td>
<td></td>
<td>Usually artificial conditions</td>
<td></td>
</tr>
</tbody>
</table>
Appendix 7.2. List of the main works performed on fish reaction to vessels, with the targeted species and the method applied. OMS: omnidirectional low frequency sonar; MBS: high frequency short range sonar; VES: vertical echo sounder; AUV: autonomous underwater vehicle

<table>
<thead>
<tr>
<th>Name</th>
<th>year</th>
<th>species</th>
<th>method</th>
<th>stimulus</th>
<th>target</th>
<th>avoidance</th>
<th>physiological stage</th>
</tr>
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8.1 Conceptual Interpretation of Results to Date
Since 1995, when the ICES CRR 209 was published, a series of noise-quieted vessels have been built. It became important to evaluate the effect of whether and how these vessels provoked a reaction in fish behavior, and whether the reaction altered surveyed abundance. These initial experimental results have been presented in the literature, and are summarized in this report.

An a priori simplifying hypothesis implicit in CRR 209 was that fish reactions to a stimulus were considered as deterministic: the same stimulus giving the same reaction. Furthermore, that noise was the most important, if not the only, source of stimuli; that a reduction in the signal would produce a concomitant reduction in fish response, and that below a threshold of 30dB above measured fish audiograms there would be no response. However, the results of experiments have not been as simple as these implicit predictions. If in some cases the fish reaction to a noise-quieted vessel was lower than to a conventional (older) vessel, in others, a stronger reaction to a noise-quieted vessel was observed. The variability of fish response to noise-quieted vessels is broad, bracketing observed responses to conventional survey vessels.

From the experimental work conducted since CRR 209 (i.e., Chapter 4), and within a broader context of sources of ship-borne stimuli (i.e., Chapter 2), fish hearing physiology (i.e., Chapter 3), and behavioral ecology (i.e., Chapter 6), we draw the following conclusions:

- The simple concepts of a blanket threshold of sound intensity below 1 kHz, and a stepped increase in reaction following a stepped increase in sound intensity, are of limited, if any, value. In large part, this is because perception, a physiological process, does not equal reaction, the result of perception, experience, and immediate ecological context.
- Reaction level appears instead to be species, environment, diel, and seasonally (i.e., following reproductive phenology) specific rather than a straightforward (linear)
function of radiated noise. Of course, radiated noise is itself a function of the physics of the medium; and perception of vessel-generated noise is a function of the sound context of the system.

- Although fish do respond to noise-quieted vessels, reaction does not appear to translate into an uncontrollable bias in abundance relative to measurements made by older, conventional vessels. That is, there is a difference between detection of a behavioural response and the assessment of abundance, namely whether the fish are changing their angle (i.e., TS) with respect to the echo sounder, and/or moving out of acoustic detection range entirely, and if so, when during the transit process (before, during, or after the vessel has passed over the school).

- Comparisons between noise-quieted and conventional (older) survey vessels can successfully control abundance biases such that stock assessments are not significantly affected in cases where newer vessels are replacing older, conventional ones.

- Although sound remains the most likely source of fish avoidance of survey vessels, the nature of the response, including: which aspects of sound fish respond to; under what conditions fish will respond; and the type, level and intensity of the response, remain poorly understood.

When considering the recommendations of CRR 209, we conclude that:

- Frequencies above 1kHz, within the range of acoustic survey equipment, are out of the detection range of most fish. Arguments in favor of maintaining this standard therefore come from other quarters than fish reaction, and are not considered here.

- The application of a simple threshold below 1kHz across all species and systems is not sufficient to positively eliminate fish avoidance.

- Investment in noise-quieted vessels may be important for reasons other than minimizing fish avoidance, including but not limited to increasing the signal-to-noise ratio, crew working conditions, and general issues of noise pollution.
8.2 Recommendations

- There is a great need for basic research (including both laboratory and field experimentation) on sound (including vessel sound) as a physiological as well as a behavioral stimulus. The variable experience with noise-reduced vessels clearly shows that the seemingly logical approach based on the 30 dB criterion was not sufficient. More knowledge about which aspects of sound fish actually react to is critical to understanding the differences between conventional vessels and noise-quieted vessels. Implicit in a more complete understanding of the reactions of fish to vessel-radiated sound is a standardized and comprehensive description of the survey platform.

- Because there are so few experimental results analyzing the effects of noise-reduced vessels on fish reactions, and those experiments that do exist suggest variable responses both among and within ecosystems/fisheries, additional comparative experiments must be designed as a function of both environmental and biological parameters in order to determine the degree, and timing relative to vessel passage, of avoidance within each survey system. These are necessary before cross-system comparisons, or more comprehensive explanatory models, can be interpreted and developed, respectively.

- In some cases, avoidance is much lower during certain periods during the 24-h-cycle, seasons, and/or in certain habitats (including depth strata). Surveys should ideally be limited to these periods and locations, and thereby minimize translation of assessment bias as a function of behavioral response to survey vessels (noise-quieted or conventional).

- Vessel avoidance does not necessarily equate to significant biases in stock assessment. Until such time as reliable models of avoidance can be constructed and tested, correction factors such as those outlined in Chapter 5 should be used.
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