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Volume 196 April 1993

Fish Behaviour in Relation to Fishing Operations

A Symposium held in Bergen,
11–13 June 1992

International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

Erratum

Hydrobiological Variability in the ICES Area, 1980–1989
ICES mar. Sci. Symp., 195: 316–325

Bakun, A. Global greenhouse effects, multi-decadal wind trends, and potential impacts on coastal pelagic fish populations

It is regretted that, because of a printing error, Figure 3 on page 319 of the above volume was reproduced without the coastline.

An amended page is printed on the reverse of this sheet for insertion at the appropriate point.

R. R. Dickson
Editor-in-Chief

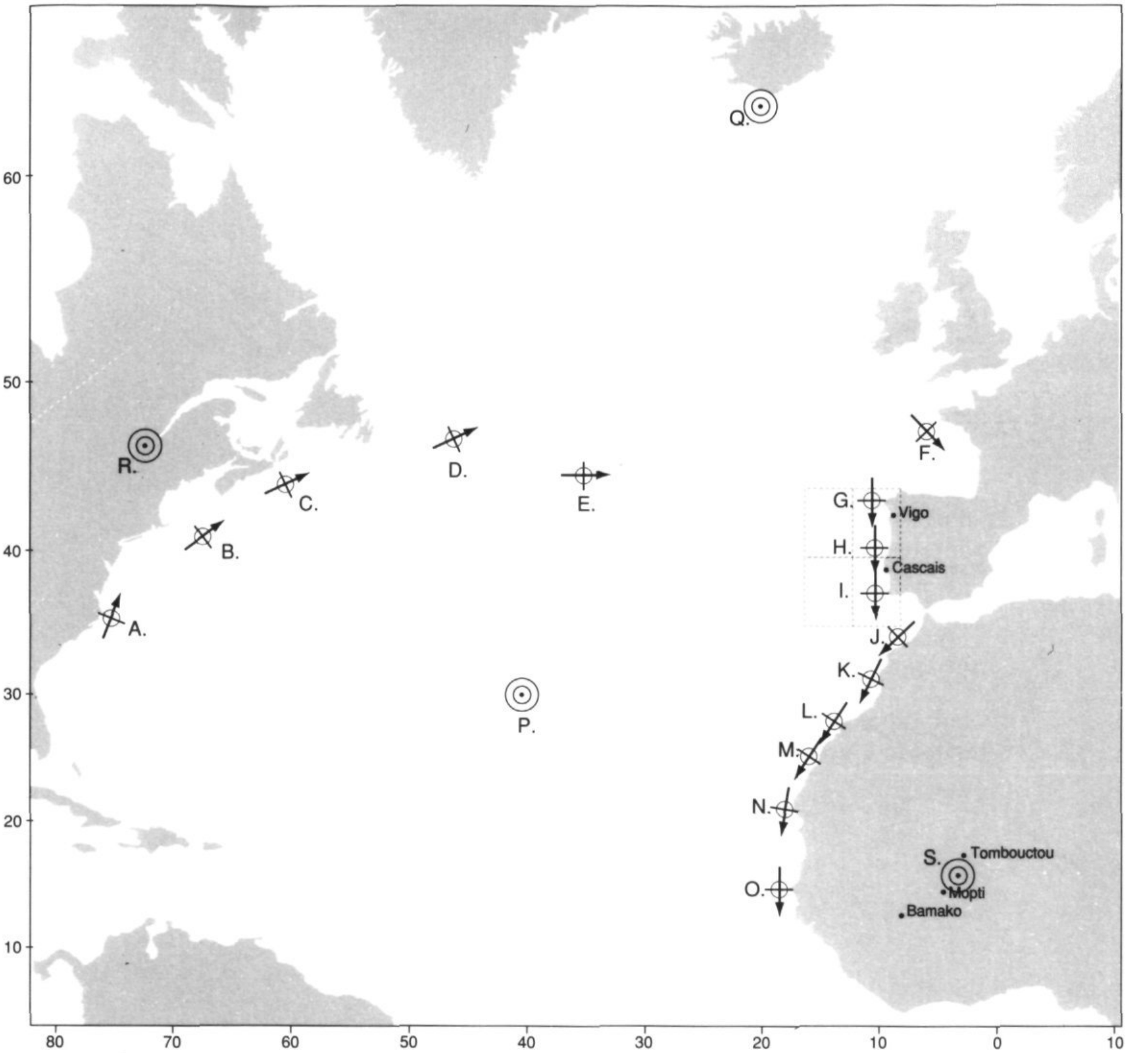

Figure 3. The North Atlantic. Locations at which time series have been constructed are indicated by the symbols (identified by capital letters to correspond to the time series plots shown in Figs. 4, 6, and 7 and to the entries in Tables 1 to 3). Arrow symbols (A to O) indicate positions of time series of stress estimates and point in the direction toward which the components treated in Figure 4 and Table 1 have been resolved. Circular symbols (P to S) indicate positions of atmospheric pressure time series treated in Figure 6 and Table 2.

performed (Table 1): (1) for the entire period, (2) for the period 1958–1973 of particularly rapid increases in several systems examined by Bakun (1990), and (3) for the period since 1973.

On the western side of the Atlantic the long-term (1946–1990) trend toward increasing alongshore windstress is highly significant at Cape Hatteras (A). The trend remains positive but becomes progressively weaker northward along the North American continental boundary (B, C), where the orientation of the coast is such that the perpendicular inland direction becomes increasingly northward, thus tending to oppose continental heating in the interior relative to the ocean area. Along the northern limb of the Gyre, where direct contact with a continental landmass is lost, the trend actually turns negative (D, E). Approaching the European continent, the negative trend diminishes to be nearly "flat" at the French coastal location (F). However, on the relatively meridional coast of the Iberian Peninsula (G, H, I) a strong, highly significant increasing trend is evident. The increase is particularly pronounced at the central location (H) where the "temperature contrast" effect of the Iberian landmass would tend to act most directly. Near the separation between the European and African continents, where the configuration of a "continental interior" is somewhat complicated by the presence of the Mediterranean Sea, etc., the increasing trend disappears (J). Note that a similar

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Selected papers from a
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Edited by C. S. Wardle and C. E. Hollingworth

International Council for the Exploration of the Sea
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Fish Behaviour in Relation to Fishing Operations

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International Council for the Exploration of the Sea
Conseil International pour l'Exploration de la Mer

Palægade 2–4 DK-1261 Copenhagen K Denmark

ICES mar. Sci. Symp., 196: 1. 1993

Fish Behaviour in Relation to Fishing Operations

Introduction

Steinar Olsen
Convener

The ICES Symposium on Fish Behaviour in Relation to Fishing Operations was held in Bergen, Norway, 11–13 June 1992. It was the first major international conference to be held on this multidisciplinary subject since October 1967, when the FAO Conference on Fish Behaviour in Relation to Fishing Techniques and Tactics was conducted in Bergen, with the active support of ICES in the initiating and planning stages.

The Symposium was organized by the Convener, Steinar Olsen (Norway), together with a Steering Committee consisting of D. L. Alverson (USA), Pierre Fréon (France), B. van Marlen (Netherlands), Kjell Olsen (Norway), and P. A. M. Stewart (UK). The meeting took place at the Natural Science Building of the University of Bergen.

The scope of the Symposium was restricted to the marine environment, with priority given to the effects of fish behaviour on fishing success, directly and indirectly. Experience and review papers were invited on three main themes: (1) Fish behaviour relevant to fish capture processes; (2) techniques of observation; and (3) application of fish behaviour knowledge. The response was most encouraging: a total of 95 titles were submitted, and, of these, 58 were accepted for oral presentation during six plenary sessions. In addition, four posters were displayed for the duration of the meeting, and nine special video presentations were given.

T. Arimoto (Japan), Å. Bjordal (Norway), and members of the Steering Committee acted as session chairmen. The following served as rapporteurs: C. W. Glass (UK), F. Gerlotto (France), R. Fonteyne (Belgium), Roger Larsen (Norway), S. Løkkeborg (Norway), and C. W. West (USA).

About half the contributions were mainly relevant to Theme 1. They addressed perceptual abilities, behavioural patterns, and physical capabilities of the fish, including their vulnerability to encounters with fishing gear, as well as attempts to synthesize and predict fish behaviour by mathematical modelling. Catch efficiency and selectivity are real-world manifestations of fish behaviour, and better understanding of natural behaviour and learning capacity is a prime topic for future research. Survival studies make it clear that conservation benefits are to be derived from selective gears, but more work is needed on interspecies differences, the effects of size and condition on survival, discard mortality, and identification of mortality agents.

Contributions specifically aimed at Theme 2, on observation techniques, were few, but many papers contained valuable new information and documented the great development which has taken place in recent years in improving methods and instrumentation for observing and monitoring fish behaviour and fishing gear performance. This progress has greatly enhanced the potential for obtaining the detailed knowledge of fish behaviour and reaction needed for developing the fishing technology that can meet the future requirements of *responsible fishing* with regard to selectivity, by-catch reduction, and survival of non-target organisms.

One-third of the contributions were directly relevant to Theme 3 and dealt with the application of knowledge of fish behaviour for developing better fishing gear and methods as well as for improving assessments and fisheries management. The work presented demonstrated that such knowledge is to some extent being applied, and the scope for utilizing insights into fish behaviour is much greater than has been realized, with respect to the development of fishing technology and to fisheries management. Thus, while attempts are most often made to solve management problems regarding by-catch of undersized fish and unwanted organisms by prohibiting certain methods of fishing, designating closed areas, etc., the same objectives might well be achieved by means of relevant basic fish behaviour studies and subsequent gear developments.

This volume contains 39 papers presented at the Symposium, selected and edited by C. S. Wardle, Scientific Editor, and C. E. Hollingworth, Technical Editor. The editing of the volume has been generously supported by liberal financial contributions from the Scottish Office Agriculture and Fisheries Department and from the Fisheries Research Council of Norway.

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ICES mar. Sci. Symp., 196: 2. 1993

Referees

The papers submitted for publication in this volume were refereed by the generous efforts of the following experts:

Arimoto, T.
Armstrong, J. D.
Arnold, G. P.
Balken, G.
Batty, R. S.
Blaxter, J. H. S.
Brothers, G.
Buerkle, U.
Carr, H. A.
Castro, K. M.
Chapman, C. J.
Dahm, E.
DeAlteris, J.
Dickson, W.
Dunkley, D. A.
Fernö, A.
Ferro, R. S. T.
Fonteyne, R.
Fréon, P.
Galbraith, R. D.
Giske, J.
Glass, C. W.
Godø, O. R.
Haan, D. de
Hall, C. D.
Hall, S. J.
Hawkins, A. D.
Helfman, G. S.
Hillis, P.
Hislop, J. R. G.
Hovgård, H.
Hreinsson, E.
Jakobsen, T.
Johannesen, T.
Johannessen, A.
Johnstone, A. D. F.
Kennedy, G.
Koeller, P.
MacLennan, D. N.
Magurran, A. E.
Massé, J.
Misund, O. A.
Mitson, R. B.
Moore, A.
Munch-Petersen, S.
Nakken, O.
O'Neill, F. G.
Pawson, M.
Porter, R.
Potts, G. W.
Reid, D. G.
Sangster, G. I.
Shearer, W. M.
Simmonds, E. J.
Soldal, A. V.
Stewart, P. A. M.
Toivonen, A.-L.
Urquhart, G. G.
Valdemarsen, J. W.
Walsh, S. J.
Webb, J.
Wileman, D. A.
Zaucha, J.

I. FISH BEHAVIOUR RELEVANT TO FISH CAPTURE PROCESSES

ICES mar. Sci. Symp., 196: 5–11. 1993

Advances in understanding of basic behaviour: consequences for fish capture studies

Anders Fernö

Fernö, A. 1993. Advances in understanding of basic behaviour: consequences for fish capture studies. – ICES mar. Sci. Symp. 196: 5–11.

Since the Conference on Fish Behaviour in Relation to Fishing Techniques and Tactics held in Bergen in 1967, our understanding of fish behaviour has developed rapidly. Based on the general premise that animals show optimal behaviour with regard to fitness, ethology and behavioural ecology have made rapid progress, e.g. by making quantitative predictions of behaviour in different situations and comparing models with observed behaviour. This paper illustrates how this new knowledge has influenced our understanding of fish capture, and suggests some important lines of future research. Formulation of specific hypotheses and better quantification of units of behaviour could improve gear and behavioural research. Differences between species and between size classes within species in the response towards gear should be given adaptive explanations, and more goal-orientated studies on swimming activity and search behaviour of commercially important species should be conducted. Variations in response to different types of gear could be explained by fish making a trade-off between conflicting demands, e.g. feeding and avoiding predation; more information on biologically meaningful background variables is therefore needed.

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Introduction

It is now 25 years since the Conference on Fish Behaviour in Relation to Fishing Techniques and Tactics in Bergen. At that meeting, our knowledge of the reaction of fish to fishing gears and of relevant aspects of the natural behaviour of commercially important fish species was summarized with the aim of stimulating contact between basic and applied research (Ben-Tuvia and Dickson, 1968). What has happened in this area during the past 25 years? Since the last conference, there has been a breakthrough in our understanding of animal behaviour, in particular as a result of the development of the discipline of behavioural ecology. What have been the consequences for gear and behavioural research?

Progress in basic research

The development of behavioural ecology has had a profound influence on our understanding of animal behaviour. Ethology has always focused on the biological function and evolutionary background of patterns of behaviour, but as a synthesis of ethology, ecology and evolutionary biology, behavioural ecology has explored these domains more systematically. Optimality theory is a powerful tool in this connection (Krebs and Davies, 1987). The assumption that animals behave optimally in relation to fitness makes it possible to predict what would constitute ideal behaviour, with which observed performance can be compared; the costs and benefits of the behavioural decisions can then be analysed. Fish are important experimental animals in behavioural ecology (Pitcher, 1986a): we now have a lot of information about the foraging, schooling, and antipredator behaviour of fishes, for example, and there are functional explanations for differences in behaviour between and within species.

Applying the findings of behavioural ecology to gear and behavioural research should present no serious problems. Except when recapturing ranched fish or catching fish in enclosures, fish capture concerns wild fish, and the behaviour of such fish should have adaptive explanations. With regard to the direct response to fishing gear, however, the assumption of optimality is to a certain extent violated. Modern fishing gear is a relatively new factor in the environment, and fish cannot be expected to have evolved optimal behaviour to deal with a capture situation, although learned avoidance reactions have been demonstrated towards both active and passive gear (Pyanov, this symposium; Fernö and Huse, 1983). In fact, fishing gear is designed to make fish behave maladaptively. One example of a maladaptive response is the reaction of fish to trawl wires, herding them into the path of the trawl (Wardle, 1986). Another example is that fish are stimulated to respond to neighbouring baited hooks on a longline by movements of already-hooked fish (Fernö *et al.*, 1986; Løkkeborg *et al.*, 1989). Still, understanding the functional significance of different patterns of behaviour will help us to explain interactions between fish and gear.

Hypotheses and predictions

A normal research strategy in behavioural ecology is to formulate a specific hypothesis, make predictions from this hypothesis, and conduct experiments or collect data to test the predictions and thus support or reject the original hypothesis (Krebs and Davies, 1987). Although it might be argued that the difference between this procedure and a more broadly defined investigation is merely of a formal nature, there is little doubt that the strict formulation of hypotheses and predictions is one reason for the marked progress that has been made in behavioural ecology.

In the study of fish behaviour in relation to fishing gear, however, this scientific procedure has seldom been used. This omission reflects the more descriptive nature of the research. Nevertheless, there is no doubt that several findings in behavioural ecology could be used to set up predictions about how fish react to fishing gear.

The behaviour of fish schools to predators is influenced by school size, with a large school reacting at a longer distance, but at a lower intensity, than a small school (Magurran *et al.*, 1985). The functional explanation for this finding is that fish in a large school are exposed to a lower risk of predation. Although results from small schools of freshwater fish cannot directly be transferred to large schools of marine fish, and fishing gears such as trawls or purse seines are not equivalent to a predator (Hemmings, 1968), one might expect on the basis of this finding that larger fish schools would display a weaker response to fishing gear. This prediction could be tested by systematically investigating the reaction of schools to gear or vessel noise in an area with a large variation in school size. This has not been done so far (but see Misund, this symposium), although it was one of the areas for future work recommended by the 1967 conference. Formulation of a clear hypothesis could have resulted in more systematic data collection on this question with consequences, e.g. for estimation of abundance by sonar (Misund *et al.*, 1992).

Quantification of behaviour

It was recognized early in the study of animal behaviour that a prerequisite for a quantitative approach is the existence of strictly defined units of behaviour. Frequency of occurrence, duration, and latency time of different behaviour patterns can then be calculated and, for example, sequence and factor analysis (Colgan, 1978) can be applied to the data. However, the necessity to rigorously define units of behaviour has not always been appreciated in gear and behavioural research, and it was not clearly identified at the 1967 conference.

There seems to have been too little quantification of defined behaviour patterns in research on gear and behaviour. The avoidance reactions of fish towards fishing vessels and gear have sometimes been well quantified. An example is the studies by sonar on positional changes of pelagic fish schools in purse seine capture situations (Misund and Aglen, 1992). With regard to reactions to fishing gear in the near field, however, most studies are qualitative rather than quantitative. An exception is the study of passive fishing gear such as long lines and traps, where quantification of defined patterns has been usual (Fernö and Huse, 1983; Fernö *et al.*, 1986; Valdemarsen *et al.*, 1977) and sequence analysis has been applied to the data (Lee *et al.*, 1989; Huse and Fernö, 1990).

Although several valuable studies have described the general behaviour of fish in the vicinity of trawls, for instance by use of low-light underwater television cameras on remote controlled vehicles (see Wardle, 1986, for a review), defined units of behaviour have rarely been used. One explanation for this omission may be the difficulty of visually observing single fish in a capture situation. However, it should be possible to observe the behaviour of single fish in the mouth of the trawl for some time in order to record behaviour patterns *vis-à-vis* the net walls and to estimate the turnover rate (the mean time the fish can keep pace with the trawl). A great many videotapes with the reactions of fish to trawls have already been collected by different institutes, and these tapes could be further analysed. With the exception of the "fountain effect" caused by otterboards (Wardle, 1986), the wide range of synchronized behaviour patterns that a fish school may display towards predators (Pitcher, 1986b) has not yet been described in a capture situation with active fishing gear. Although the practical difficulties must be appreciated, there seem to have been few attempts to describe, define, and quantify actual reactions to gears, whether of single fish or of schools.

Trade-off explaining variation in response

The relationship between stimulus and response determines the outcome of a fishing operation, and the reaction to different stimuli was a central theme of the 1967 conference. There were several reports on the absolute thresholds of reaction of different senses, and many detailed studies of sensory capacities have been made since then (see Atema *et al.*, 1988; Douglas and Djamgoz, 1990). Sensory physiology studies are essential if we are to understand the reaction of fish to stimuli and to explain, for example, the differences between day and night catches (Engås and Soldal, 1992). However, in order to demonstrate optimal behaviour, a fish must respond selectively to changes in the environment. At the 1967 conference, it was already being stressed that the response to a certain stimulus varied according to the physiological state of the fish, sex, and previous exposure to the stimulus.

Although rather simplified, this view of how fish react to different stimuli was in line with basic knowledge of that time. A large amount of work on the causes of variation in response had been performed in the 1950s and 1960s in different animal groups, including fish (see Hinde, 1970 for a review). These studies demonstrated, for example, that repeated stimulation without reinforcement had complex effects on responsiveness, often initially inducing an increased effect (sensitization), but with further stimulation resulting in a decreased effect (habituation). Some of this basic knowledge might have been used more actively in gear and behavioural research, as the effect of repeated stimulation is central to fish capture, for example in connection with repeated exposure to the noise from fishing vessels. The relationship between stimulus and response is, however, complex, and the variation in response to fishing gear in the field is not as easily analysed, as it might appear as though "also under precisely controlled conditions the animal does as it damn pleases" (Dubos, 1971).

Our understanding of the functional aspects of response variation has improved during the past decade. It is now well documented that fish, like other animals, often make a trade-off between different demands, such as the need for food and the risk of predation (Milinski, 1986). This compromise is influenced by the situation, with increased hunger resulting in less vigilance for predators and increased predation pressure leading to a weaker response to food (Milinski, 1986). The dynamic properties of this trade-off are shown by the finding that animals can accept higher risks in order to reproduce earlier (Aksnes and Giske, 1990). The direction of the changes can thus be explained, but it is difficult to make quantitative predictions about the size of the changes involved when different currencies of fitness are involved (mortality risk versus energy gain, Milinski, 1986).

Some early observations demonstrated the existence of a trade-off in the reaction of fish to fishing gear. For instance, schools of herring showed a weaker reaction to pelagic trawls when spawning (Mohr, 1964) and sardines noticed a trawl at a later stage in the presence of prey (Radakov, 1973). But trade-offs between different demands have not been systematically used to explain variations in response towards fishing gear. Gears will not generally be perceived as predators by fish (see later), but at some stages of the catch process most gear produce stimuli that could frighten the fish. An approaching trawl might cause an avoidance (Wardle, 1986), and fish in the vicinity of baited hooks come into a conflict between approach and withdrawal, that could lead to inhibited responses without physical contact with the bait (Fernö *et al.*, 1986; Løkkeborg *et al.*, 1989). Variation in response towards fishing gear could therefore often be explained by a trade-off between different factors.

A trade-off between the energy content of the prey and the handling time explains why there is a preferred prey size in fish (Kislalioglu and Gibson, 1976). Knowledge that there is an optimal prey size could have been used more actively when testing different bait sizes in long-line fishing trials. An alternative starting point to the bait size used in the commercial fishery could be the mean mouth diameter of the fish in the area, as it is known that handling time increases rapidly when this limit is approached (Kislalioglu and Gibson, 1976).

If we wish better to understand variation in response to gear-induced stimuli, we must have more information on the biological situation of the fish. Background data on hunger level, predation pressure, and state of maturity should be systematically collected. The response intensity of cod and whiting to baited hooks, recorded as the proportion of fish caught by swallowing the hook instead of getting hooked in the mouth, has for instance been shown to be influenced by systemic appetite factors such as condition factor and liver weight (Johannessen, 1983; Fernö *et al.*, 1986).

Knowledge of natural behaviour – a bottleneck

It can be argued that more research has been devoted to determining the limits of achievements of sense organs and muscles than to finding out what fish actually do in a catch situation. Knowledge of the maximum and sustainable swimming speed of different species (Blaxter, 1968; He and Wardle, 1988) is crucial to our understanding of how trawls catch fish, as fish will swim to their limit to avoid contact with such gear. With regard to passive fishing gears, however, the absolute limit of swimming speed is less important than what fish actually do.

It is now time to devote increased efforts to the study of natural behaviour with the specific aim of obtaining more knowledge of fish capture. Development of suitable techniques, such as small and durable acoustic tags (Hawkins and Urquhart, 1983) and split-beam echo sounders capable of following individual fish (Ona, this symposium), together with the development of optimal foraging models (Krebs and Stephens, 1986), opens up new possibilities here.

Fish can be classified along a continuum from "sit and wait" to widely foraging predators, and can in theory follow different search strategies in order to localize a resource (Bell, 1990). The spontaneous level of activity of fish determines the probability of their coming into contact with stationary gear such as nets. The search path, threshold of reaction to chemical stimuli, and swimming speed during the localization phase determine the outcome of fishing operations with traps and long-lines. These fields of research have so far been virtually neglected. Systematic studies using acoustic tagging and split-beam echo sounders should be made.

The presence of prey can have a marked effect on search behaviour. The linear distance travelled by sticklebacks decreased significantly when food was found and eaten, leading to area-restricted searching (Thomas, 1974). Feeding generally reduces the scope of activity in fish (Soofiani and Hawkins, 1982). One might therefore postulate that low food availability in an area should lead to an increased probability of coming into contact with stationary gear such as gillnets. For long-lines and traps this tendency could be even stronger. Fish primarily localize an odour source by positive rheotaxis (Atema, 1980; Løkkeborg *et al.*, 1989), and as both the leaching rate of the feeding stimulant from the bait, and current speed and direction vary, it can be difficult to localize the stimulus source (Olsen and Laevastu, 1983). A fish perceiving a chemical cue must decide whether or not to seek and utilize the resource, and a hungry fish could be expected to take a higher risk of wasting time in ineffective search. It could therefore be predicted that the probability of coming into contact with passive gear ought to increase as the availability of food in the area decreases. For long-lines and traps we should expect an even greater catch of unsatiated fish, as such fish are less selective (Beukema, 1968) and ought to pay less attention to frightening stimuli from the gear in a trade-off situation.

Knowledge of the distribution of fish in time and space is crucial to fish capture. The importance of the horizontal and vertical distribution of fish has long been recognized. In spite of technological advances, localizing fish in the horizontal plane can still be a problem. To localize fish in the vertical plane presents no problem, although the depth of the fish can limit accessibility with different gears. A trade-off between food intake and predation risk often seems to determine vertical distribution (Clark and Levi, 1988). Although we have a lot of information about vertical migration and day versus night catches on commercially important fish species (e.g. Beamish, 1966; Engås and Soldal, 1992), more knowledge of the vertical distribution is important when we try to obtain representative samples of fish populations (Engås and Godø, 1989). Differences in depth preferences between subgroups of a species, for example with regard to size (Boudreau, 1992), can have strong consequences in this respect.

The comparative approach

By categorizing different species according to the way they behave to fishing gear and trying to identify the underlying biological adaptations that cause the differences, a better understanding of why a species behaves in a given way might be achieved. This would provide a better opportunity to influence behaviour in a catch situation in the desired direction. In research on gear and behaviour, however, this comparative approach has not yet been systematically employed.

Okonski (1968) tried to categorize the behaviour of different fish species in relation to trawls in different ecological groups, but this work included few observations and does not seem to have been followed up. It is now well known that different species show marked differences in their responses to trawls, with haddock, for example, rising above the trawl, while cod remain near the sea bed (Wardle, 1986). No adaptive explanation to this difference, for example based on differences in the antipredator behaviour of cod and haddock, has been offered.

Also for other types of fishing gear, the comparative approach has been of too limited use. The difference in behaviour of cod and haddock towards long lines, however, has been explained by an interspecific difference in foraging behaviour: cod take active prey and show a more intense but more selective reaction towards baited hooks than do haddock, which live on slow-moving or benthic prey (Løkkeborg *et al.*, 1989).

The usefulness of the comparative approach depends on a better understanding of which naturally occurring behaviour patterns are triggered by a given type of fishing gear (Hemmings, 1968). The gear usually releases more than one specific reaction. For instance, in the response to trawls, both the optomotor reaction and the escape reaction are involved (Wardle, 1986).

Individual differences

The behaviour of fish to fishing gears is usually regarded as species-specific. Variations in behaviour caused by season or reproductive state have been recognized, but individual differences have not been studied. An exception is the work by Solemdal (1984) on bait preferences in cod, in which individual differences were partly explained in terms of previous experience. Marked differences between individual fish of a single species in different aspects of behaviour have now been demonstrated (see Magurran, 1986 for a review). The optimal strategy of an individual may depend on size, earlier feeding specialization, and the behaviour of other individuals.

Size is an important reason for differences in the behaviour of individual fish. Fish of different sizes are faced with different situations with regard to both prey and predators. Larger fish may have a greater ability to detect food (Breck and Gitter, 1983) and shorter handling time, and be less vulnerable to predators. The experience of predators and prey ought also to depend on size. A possible explanation for the finding that small cod preferred natural shrimp baits to shrimp-flavoured artificial baits even though artificial baits were equally effective for large cod could be that large cod have a greater diet width because of their greater experience (Løkkeborg, 1990). An alternative explanation is based on the fact that fish are in a kind of conflict when approaching a bait (Fernö and Huse, 1983), in that they must balance feeding and risk of predation. The relative weight of the different factors may depend on size, with small cod being more easily frightened by an unknown stimulus.

Size selection by fishing gear is often primarily regarded as the outcome of mechanical sorting or differences in swimming speed. However, large and small fish may differ with regard to their reaction distance (Korotkov, 1984) and this difference may well influence selectivity. Other aspects of behaviour might also influence size selection. The greater size of Norway lobster caught in traps than in trawls has been explained by a two-stage selection process, with small individuals being attracted from within a shorter range than large individuals, and in addition being chased away from the pots by larger, more aggressive individuals (Bjordal, 1986). Likewise, large fish are believed to have a higher probability of coming into contact with a longline than small fish because of their larger feeding range (Hamley and Skud, 1978). Fishing is now so efficient that one of the best things behaviourists can do is to improve selectivity to eliminate under-sized fish.

Gear-induced physiological, behavioural, and genetic changes

The study of fish behaviour in relation to fishing gear has primarily been concerned with improving the efficiency and selectivity of the gear. Fishing gear, however, has become an integral part of the environment of commercially important species and should be expected to affect the whole suite of adaptations to the surrounding environment.

Fishing gear may be seen as stressors influencing fish that are not caught. Fish that escape can be so severely injured that they die (Main and Sangster, 1990), but smaller effects can also have consequences for fish capture. Fish that have escaped from a trawl may be exhausted for at least 24 h (Batty and Wardle, 1979), and complete recovery from hooking can take several days (Wydoski *et al.*, 1976). Stressed fish react at shorter ranges (Järvi, 1989), and fish in a heavily fished area might thus be expected to show a weaker response to the gear. This could result either in increased catchability, for example by slower escape reactions to the trawl nets, or in decreased catchability through a weaker herding effect of trawl sweeps or reduced reaction to gear based on attraction. The risk of succumbing to natural predators may also be increased by the stress that results from fishing activity.

Heavy fishing pressure may also influence habitat preferences. Such preferences are believed to be the result of adaptive decisions, where the advantages and disadvantages of the different habitats are weighed. The presence of predators has been shown to lead to a shift to a suboptimal habitat in sunfish (Werner *et al.*, 1983). Fishing, in particular with active gear, may be a similar negative factor, causing fish to move to areas where they are less available for fishing.

Most fisheries are now so efficient that they are the major component of mortality (Moav *et al.*, 1978). This could lead to genetic selection effects by fishing, although such changes are difficult to demonstrate (Allendorf *et al.*, 1986). Reaction to fishing gears might be affected. A possible example of genetic changes in avoidance behaviour toward nets has been observed in the pond-cultured Chinese carp (Wohlfarth *et al.*, 1975). That selection on behavioural traits can have significant effects in fish is demonstrated by differences in schooling behaviour between populations of a species that have been subjected to different predator pressures (Seghers, 1974). The optimal trade-off between feeding and vigilance for predators also seems to be influenced by selection (Fraser and Gilliam, 1987), and such changes could have important consequences for reactions to gear. Genetic changes may also influence life-history parameters, and size-selective fishing may decrease the growth rate of fish populations (Ricker, 1981). Dividing the total fishing pressure between several different types of fishing gear would make such selection less consistent.

Conclusions and suggestions

The 1967 conference produced a large amount of information on basic fish behaviour, and it was suggested that the relationship between natural behaviour and behaviour in relation to fishing gear should be explored in more detail. Even though a great deal has been done, there has been little research along several of the proposed lines. Furthermore, since 1967 there have been revolutionary changes in our understanding of animal behaviour, but to date this basic research has influenced research on gear and behaviour to only a limited extent. The following suggestions are made for future work:

- Methods successfully used in behavioural ecology, based on the formulation of specific hypotheses and predictions, should be applied to gear and behavioural research. This approach could result in more goal-orientated data collection and more systematic studies on the complex interaction that takes place between fish and gear. The behaviour of fish, particularly in relation to active fishing gear, should also be better quantified by use of rigorously defined units of behaviour.
- Variations in response to gear-induced stimuli could be explained by fish making a trade-off between conflicting demands, especially between feeding and avoiding predators, with the situation of the fish determining the relative weight of the different factors. To that end, more information on biologically meaningful background variables should be collected, for instance on stomach content and predation pressure in the area.
- Species differences in behaviour in relation to gear could be investigated using the comparative approach, regarding the behaviour of a species as a suite of adaptive responses to the environment. By adopting this strategy, we could progress from a purely descriptive approach, and classify species in different ecological groups.
- In addition to interspecific differences there are also intraspecific variations in behaviour, caused by individual differences in size, state of maturity, and feeding specialization. Such differences have important consequences for the selective properties of fishing gears.
- As our knowledge of the direct response to fishing gear increases, it becomes ever more important to learn more about the natural behaviour of fish. Although this need has long been recognized, there have been few goal-orientated studies on the behaviour of commercially important species without the influence of fishing gear. Progress in our understanding of basic behaviour, and technological advances that make it easier to observe the behaviour of both single fish and schools in the natural environment, create an ideal situation for studies of natural behaviour. Such studies would provide valuable knowledge of what fish actually do with regard to thresholds of reaction and swimming activity, which is often more important than knowledge about limits of achievement.
- The study of fish behaviour in relation to fishing gear should not only deal with making gear more effective and selective, although this is still of great importance. The effect of fishing with various types of gear on different aspects of exploited fish populations, including physiological loads, habitat preferences, and genetic changes, should be investigated in more detail.

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Fish learning in response to trawl fishing

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Changes in defensive behaviour adaptive to trawl fishing were studied in some freshwater fish species under natural and experimental conditions. Under natural conditions, repeated hauls of a trawl were made across aggregations of bream (*Abramis brama*) and individuals were tracked with ultrasonic transmitters. In aquarium experiments, a small scale model trawl and two dip nets of different sizes were used for catching lemon and white tetra (*Hemigrammus caudovittatus*) and rosy barbs (*Barbus conchonius*). Conditioned avoidance reactions to the fishing gears were established in the bream under test after one to two hauls. The reaction was weak in young bream and strong in adults. Experienced individuals escaped from the path of the trawler at a distance of about 50 m before it reached them. The results of the aquarium experiments confirmed and augmented those obtained under natural conditions.

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Introduction

Fishing is the oldest anthropogenic factor influencing populations of many fish species. However, to date the question of fish behavioural adaptation to this factor has remained practically uninvestigated, although it is well known that defensive fish behaviour significantly influences the success of fishing.

Innate unconditioned reactions and learned avoidance both influence fish defensive behaviour. It has been experimentally shown that fish as well as higher vertebrates can easily acquire conditioned reflexes to any external stimulus for which these animals have corresponding receptors (Frolov, 1925). The speed of acquisition of a simple conditioned reflex is approximately equal in all vertebrates (Voronin, 1954).

Having observed fish behaviour during fishing, some scientists raised the possibility that fish might have conditioned defensive reactions to active fishing gear (Golenchenko, 1955; Kuhorenko, 1977).

It is well known that birds and mammals quickly learn to avoid hunters (Severtsov, 1922; Illichov, 1977). This kind of learning in fish has been demonstrated only as far as angling is concerned (Beukema, 1970; Fernö and Huse, 1983), so I report here an attempt to investigate learned avoidance in fish to active fishing gears under natural and experimental conditions.

Investigations under natural conditions

In this work data on trawl catches of bream (*Abramis brama* L.) were used as well as echograms and tracking experiment data on individuals tagged with ultrasonic transmitters. These investigations were part of a study in 1979–1985 on spatial and temporal distribution of bream in Votkinskoe reservoir, an area where commercial trawl fishing has never been practised before.

A trawler of 180 reg. tons and 150 h.p. engine was used, equipped with a bottom trawl having 10 mm minimum mesh size and 18 m between otter boards. Repeated tows through the same fish aggregation were carried out at intervals from 1.5 h to 3 days, and tows were also shifted to be parallel to each other. The duration of tows ranged from 5 to 20 min. The distances between parallel tows varied from 15 to 50 m. Catches (fish/hectare) in 34 sets of two hauls and in 13 sets of four hauls have been compared.

Individual bream were tracked according to the standard underwater telemetry method. "Pinger" transmitters 35 × 17 mm were used. Ten bream of 25–48 cm and 0.5–2.8 kg were caught with trawl and gillnets for tagging. All 10 tagged fish were released at their place of capture. After that, attempts were made to catch them in the trawl some time later (from 30 min to 9 days). Two or three trials were made with each individual. Tracking

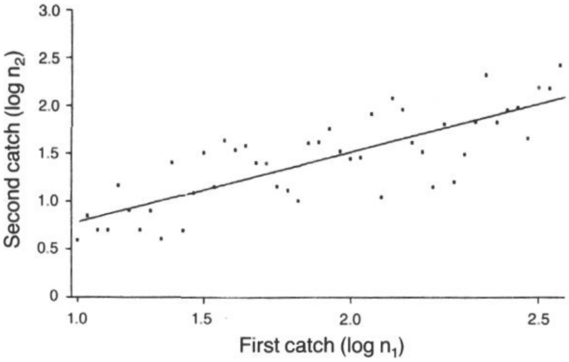

Figure 1. Dependence of the second trawl catch upon the first one in consecutive trawlings in the same area.

data on 20 other individuals tagged in the fishing area and nearby have been analysed.

Additional data on fish behaviour and distribution during the hauls were obtained with an echo sounder, model "Skipper-406" (50 kHz).

There was no commercial trawl fishing at Votkinskoe reservoir; the main fishing gears used by local fishermen were gillnets and basket traps. Bream aggregations were located in the channel zone of the reservoir at a depth from 8 to 14 m; this channel is the navigation route for vessels on the reservoir.

Comparing results of consecutive hauls through the bream aggregations, it was found that the second catch (log n_2) was lower than, and depended significantly upon, the first one (log n_1) ($r = +0.81, p < 0.01$) (Table 1; Fig. 1). No correlation was found between the second and third catches (log n_2 and log n_3), nor between the third and fourth catches (log n_3 and log n_4) ($r = +0.27$, $p > 0.05$; $r' = +0.31$, $p > 0.05$ respectively).

The dependence of log n_2 upon log n_1 regarding two parallel transects, one of them being shifted some distance horizontally from the other, was tested. Catches from two groups of hauls (10 and 19 pairs) were tested; the distance between transects was 8–10 m and 15–25 m respectively (Table 1). Correlation coefficients for log n_2 and log n_1 in these groups were $r = +0.96$ ($p < 0.01$) and $r' = +0.80$ ($p < 0.01$). The difference between these groups is not significant (*t*-test). So, the dependence of the catches occurred even when the parallel shift of the second tow was 8–25 m from the first one, though the zone of trawl capture (distance between the trawl boards) was 17 m.

Table 1. Average fish catches in consecutive trawl tows through bream aggregations.

Haul order	No. of tows	Average no. of fish caught per tow	s.e.	s.d.
Pair series:				
First catch	47	118.7	16.8	107.8
Second catch	47	43.4	7.8	50.2
Long series:				
First catch	13	127.4	34.3	123.7
Second catch	13	57.7	23.1	73.2
Third catch	13	45.6	14.8	53.4
Fourth catch	14	40.1	12.1	36.2
Laterally shifted hauls:				
8–10 m				
First catch	10	178.2	52.8	158.5
Second catch	10	71.5	27.9	83.7
15–25 m				
First catch	19	101.0	15.7	71.8
Second catch	19	50.8	10.3	47.1

Bream aggregations consisted of fish from 3 to 17 years old. Analysis of the size and age structure of this species revealed a trend towards a decrease in the proportion of adult individuals in the second trawl catches (Fig. 2). For bream less than 22 cm long (juveniles), the value of the ratio between second and first catches log (n_2/n_1) fluctuated about one.

Thus, as a rule, the first catch from a bream aggregation greatly exceeded subsequent catches, both in fish quantity and in mean fish length.

The control was as follows. At first, the vessel passed above a fish aggregation without trawling, and then towed the trawl in midwater. After that, consecutive hauls were carried out. The changes of catches in the control (six tests) and in the experiments appeared to be the same.

The quantity and distribution of fish, before and after hauls, were registered in a series of tows with an echo sounder fitted on the vessel. On the basis of these data a catchability coefficient (CC) was calculated: $CC = n/N \times 100\%$, where n is the catch and N is the fish quantity in the trawl path. Some patterns of catchability changes are shown in Figure 3. In the daytime some bream located close to the bottom were not recorded, so the CC in the second example (day after first haul) turned out to be more than 100% (Fig. 3). However, for the present purposes it is not the absolute values that are of importance, but the trend of their changes.

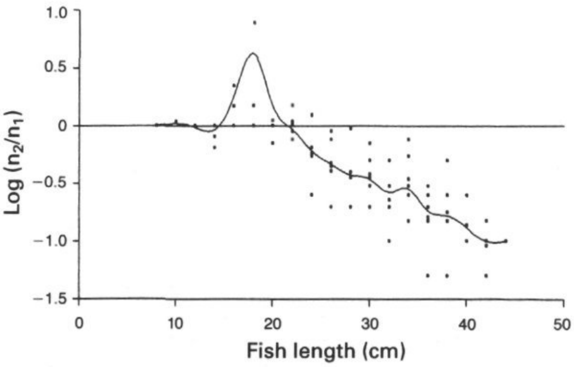

Figure 2. Change in the value of the ratio of the second catch to the first one in different size groups of bream.

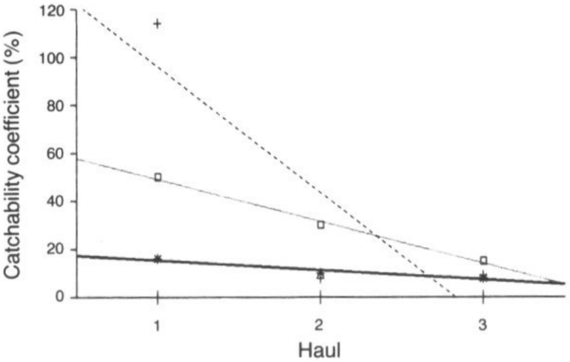

Figure 3. Change of the catchability coefficient in consecutive hauls. ∗ – during one day; + – in the next day after the first haul; □ – during one night. Haul number 1 is first, and so on.

Defensive schooling behaviour is unknown in bream; probably they escape danger individually. Moreover, fish can react to danger by detecting the signals of other escaping fish and their panic movements (Gandolfi *et al.*, 1968). Accordingly, experiments were conducted on individual bream tagged with ultrasonic transmitters.

It was found that all tagged fishes, once captured in the trawl, avoided it at the second encounter. They started to move away from the approaching trawler in advance, at about 50 m from the vessel. Three types of fish manoeuvres were noted: movement to coastal waters (four fish), movement from the shore to the open area (four fish), and escape in the direction of the vessel movement (two fish). Bream that had been caught once avoided the trawler both 0.5 h and 9 days after their release. In five cases, tagged bream swam in a new fish aggregation. The tagged bream avoided the trawler, while many fish in the same aggregation were caught in the first haul. A decrease in catch occurred in consecutive hauls.

Some other data were obtained with fish tracking: 18 out of another 20 tagged fish left the fishing area during the 24 h following release, and the other two stayed there for two days and then left.

Aquarium experiments

The two strains of tetra (*Hemigrammus caudovittatus* L.), lemon and white, and also rosy barb (*Barbus conchonius* Hum. buch., 1922) were used. Conspecific individuals belonged to one generation.

A group of 106 lemon tetras, 15–30 mm body length, was placed for two months before the experiment in an aquarium 96 cm long and 38 cm wide, with a water depth of 42 cm. Two dip nets, small white (11.5 × 11.5 cm) and big black (19.5 × 19.5 cm), were used for catching lemon tetra. Four series of trials were conducted at 3 day intervals. Each series consisted of three trials at 3.5 h intervals. Each trial consisted of five catches at 10 s intervals.

The experiments with white tetra were performed in a tank 500 × 70 × 35 cm. Two groups, 117 and 100 fish, 25–45 mm long, from one aquarium, were used. The first group was transferred with water from the aquarium to the tank. Fish in the second group were captured with a lift net and with a dip net. Food was used to attract fish into the lift net. In the experiment, white tetra were captured with a 1:30 scale model of the 18 m bottom trawl. Two series of trials in each group, consisting of three trials (hauls) at 1.5 h intervals, were carried out at 5 day intervals between series. Food was used to aggregate fish in the middle of the tank for trawl fishing.

Rosy barb, 589 fish, 25–40 mm length, were raised in an aquarium 273 × 97 × 45 cm from birth and had never been caught before the experiment. The fish were captured with the same scale model trawl as used for white tetra. In all, three trials at intervals of 1.5 h were carried out.

The velocity of gear movement was about 0.5 m s^{-1}. Captured fish were not used in further trials. Fish behaviour was recorded with a video camera.

Originally the lemon and white tetra were widely scattered and barbs gathered into a "ball". No reactions were observed in lemon tetra to the appearance of an operator, but they gathered around the net. White tetra at first reacted to the operator and to input of food by fleeing, but soon most of them aggregated at the feeding place. Barbs reacted to the operator by approaching him.

After the first haul and during the next hauls, both tetras displayed school defensive behaviour. Lemon tetra made loop-manoeuvres, avoiding the net. White tetra and barb started to avoid the trawl model when the distance from the centre of the fish aggregation (or "ball") to the trawl became very short.

Both tetras continued school behaviour, whereas the "ball" of barb dissociated for some time after the end of catching. These species restored their original distribution in 3–5 min after the end of the trial.

In the third trial lemon tetra, and in the second trial white tetra and barb, changed their defensive behaviour: they came to form a school, to escape when the operator and gear appeared (lemon tetra) and to increase avoidance distance to the trawl (white tetra, barb). The quantity of white tetra gathering at the feeding place decreased from about 80% in the first trial to 5–10% in the last trial. They began to scatter from the feeding place just after the trawl began to move (probably reacting to the noise).

The values of catches and catchability coefficient tended to decrease in successive hauls (Figs. 4, 5, 6). For white tetra in series 1 the catch was 20 fish and in series 2 it was 5. In the dynamics of lemon tetra catches in all trials, two phases could be distinguished. The biggest values of catches and of the catchability coefficient were at the start of fishing and when the new, larger net was tested. Then the values of these indexes decreased (Fig. 7).

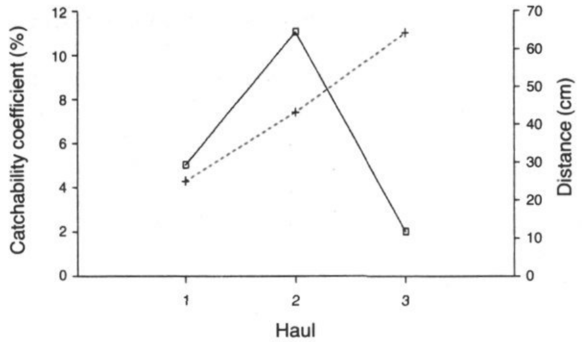

Figure 4. Changes in the trawl model catches and in the distance of fish escapement in the first series of hauls on white tetra. □ – fish catch; + – escape distance, cm.

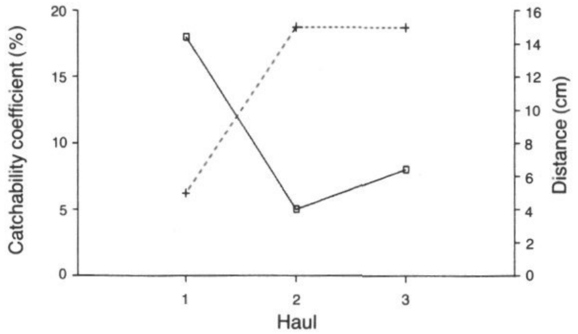

Figure 5. Changes in the trawl model catchability coefficient (□) and in the distance of fish escapement (+) in hauls on barb.

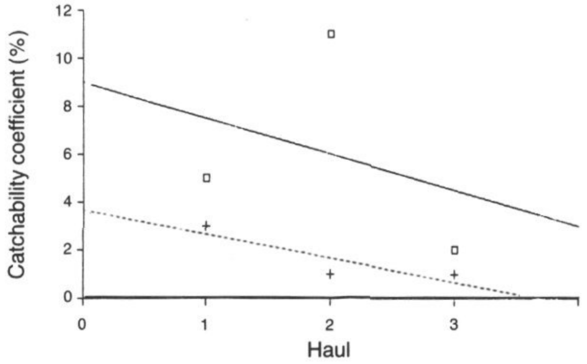

Figure 6. Changes in the trawl model catchability coefficient (%) in experiments on white tetra. □ – exp. No 1; + – exp. No 2. See text for explanation.

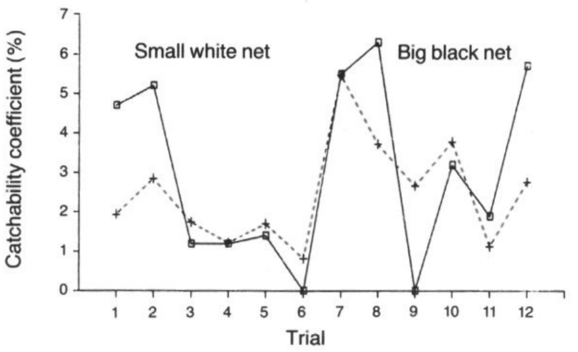

Figure 7. Changes in the catchability coefficient (%) for two dip nets in experiments with lemon tetra. □ – coefficient of the first catch in every trial; + – average coefficient in the trial. The black net was introduced in trial 7.

The lemon tetra in an aquarium situated near that in which the experiments with lemon tetra were carried out did not react to the operator's actions. The white tetra of group 2 displayed an avoidance reaction to the input of food and to trawl-model noise from the start to the end of the experiment. They did not aggregate at the feeding place. Eight fish were caught in series 1, and seven in series 2.

Discussion

Using consecutive hauls and shifting one haul in parallel to the other, it was shown that only the second catch in a series was reduced greatly, but not the third or the fourth and that this second catch reduction occurred in an area three times greater than the trawl capture zone. Therefore, a thinning of the bream aggregation by the big first catch could not be the only cause of the decrease in the second catch.

The time intervals between the trawl hauls varied from 1.5 h to 3 days, and 3 to 8 days were necessary to restore the large first catch and observe once again the reduction in the second catch. It is well known that after cessation of action of a sudden stimulus, fish under natural conditions will soon restore their original distribution pattern. Under the experimental conditions, the initial distribution pattern was restored within 3–5 min after hauling. Hence, frightening fish during the first haul could not be the only reason for the second catch decrease in parallel hauls.

Echo-location data showed that fish quantity was hardly changed after the first haul. At the same time the trawl catchability in consecutive hauls decreased. Similar data were reported by other researchers for a marine fishing area (Zaferman and Serebrov, 1989). Hence, one more cause of the reduction of the bream catches was a decrease of fish vulnerability to the bottom trawl.

The tagged bream avoided the trawler from a long distance. They left the fishing area after their release, but at the same time avoided the fishing vessel. Some of them were found in other areas 3–25 days later and did not leave those fishing areas, but still avoided the trawler. Malinin and Linnick (1983) investigated the defensive behaviour of 16 tagged bream. Some of them were captured for tagging with a trawl and others with gill nets. Individuals taken from trawl catches subsequently avoided the trawler from about 50 m. Tagged fish that were originally caught with gill nets demonstrated a herding reaction to the approaching trawler and were caught by the trawl.

More conclusive data were obtained on the tagged bream fished by the trawl in fish aggregations. Both the avoidance reaction of tagged fish and a sharp decrease of the trawl catches could be observed. Similar data on five bream have been obtained by another researcher (V. G. Yezov, pers. comm.).

A change in defensive behaviour of fish after they were caught by trawl for the first time is evident from these data. This change resulted from individual experience and was retained for not less than nine days. It served to increase survival of the fish, i.e. it could be considered as adaptive.

Bream and other species react to the approaching trawl from 1–2 m when the water transparency in reservoirs is 1.0–1.8 m (Fortunatov, 1959). It was confirmed in the aquarium experiments that fish avoided gear from a very short range during the first haul, but in the next hauls increased the avoidance distance greatly. The behaviour of bream changed after the first (second) haul. Subsequent catches were very small and consisted of young fish during the next few days. The dynamics of catches and catchability coefficients in aquarium experiments and under natural conditions were similar.

Aquarium data, of course, cannot be equally transferred to a natural situation. But only those behavioural patterns which were frequently observed under natural conditions, especially in studies of predator-prey relations, were used. In the experiments, fish displayed reactions to fishing gear that are well known as reactions to a predator: gathering into a defensive school, "loop"-manoeuvre of the school, increasing avoidance distance, and escaping a dangerous place. Fish learn to produce these reactions after 1–2 attacks by a predator (Leschova and Zhuikov, 1989). So, it appears that fish learn to react to active fishing gear in the same way as to a predator.

Thus summing up the data discussed above, it is concluded that fast learning (1–2 trials) is the basis of the adaptive changes in fish behaviour resulting in defensive reactions to trawl fishing.

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Study of learning capabilities of tropical clupeoids using an artificial stimulus

Marc Soria, François Gerlotto, and Pierre Fréon

Soria, M., Gerlotto, F., and Fréon, P. 1993. Study of learning capabilities of tropical clupeoids using an artificial stimulus. – ICES mar. Sci. Symp., 196: 17–20.

Learning capabilities of a small tropical pelagic fish, the thread herring (*Opisthonema oglinum*), were studied under experimental conditions. The conditioning consisted of associating a series of three sound pulses with a stress (hoisting a horizontal rigid net from the bottom to the surface). Individual sensibility and school stability measures indicate that fish can be stress-conditioned. Furthermore, these conditioned fish, when mixed with non-conditioned fish ("naïve" fish), can lead reactions in a school. The results and their influence on fishing are discussed.

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Introduction

Schooling behaviour in fish has been advanced as a mechanism that allows the individual to reduce the risk of predation (Pitcher, 1986). According to several authors (e.g. Hollis, 1984), the function of Pavlovian conditioning is to enable the animal to optimize interaction with biologically important events. The performance of a conditioned response allows the animal to deal better with food, rivals, predators, and mates. To investigate the importance of individual learning to fishing operations, the conditioning capabilities of a coastal tropical clupeoid, thread herring (*Opisthonema oglinum*), and the effect of the stimulated reaction of these fish on naïve fishes in a mixed school were studied under experimental conditions.

Material and methods

This study was carried out in Martinique (French West Indies). The fish were caught by day in front of the laboratory with a small liftnet and were transported to two tanks (4 m diameter and 1.6 m height) under light anaesthesia and heavy oxygenation so as to limit stress. These tanks were supplied with filtered sea water by open circulation and were strictly identical in shape and colour. An underwater loudspeaker was arranged to transmit the same sound to both tanks. A sliding, rigid net was laid on the bottom of the first tank (tank with net: tank WN). The second tank had no such net or loudspeaker (tank B). Thirty-five fish were allowed to settle in each tank. A prophylactic antiseptic treatment was applied during the two first days of acclimatization.

The experiment consisted of three phases: a 4 day habituation phase, a 10 day conditioning phase and a 2 day transmission with extinction phase.

During the habituation phase, 27 sets consisting of three sound pulses of 10 s duration each, separated by 10 s intervals, were emitted. Each pulse of 500 Hz frequency increased progressively in amplitude and stopped suddenly at the maximum value. The sound sets were applied randomly during daytime.

Before the conditioning phase, we removed the 35 fish from tank B to a raceway. In tank WN, we associated the sound pulses previously described with a stress, following in this way a classical aversive conditioning procedure. The stress consisted of hoisting the net close to the surface 5 s after the last pulse and maintaining it at the surface for 10 s. This stress was applied 22 times at random times during daytime about three times daily (the conditioning phase ended when all the fish reacted to the first sound pulse). The series of sound pulses represents the neutral or conditioned stimulus (CS), and the hoisting of the net represents the absolute or unconditioned stimulus (UCS).

During the transmission and extinction phase, the conditioned fish were mixed with the naïve fish in the two tanks. The CS without the UCS was emitted 10

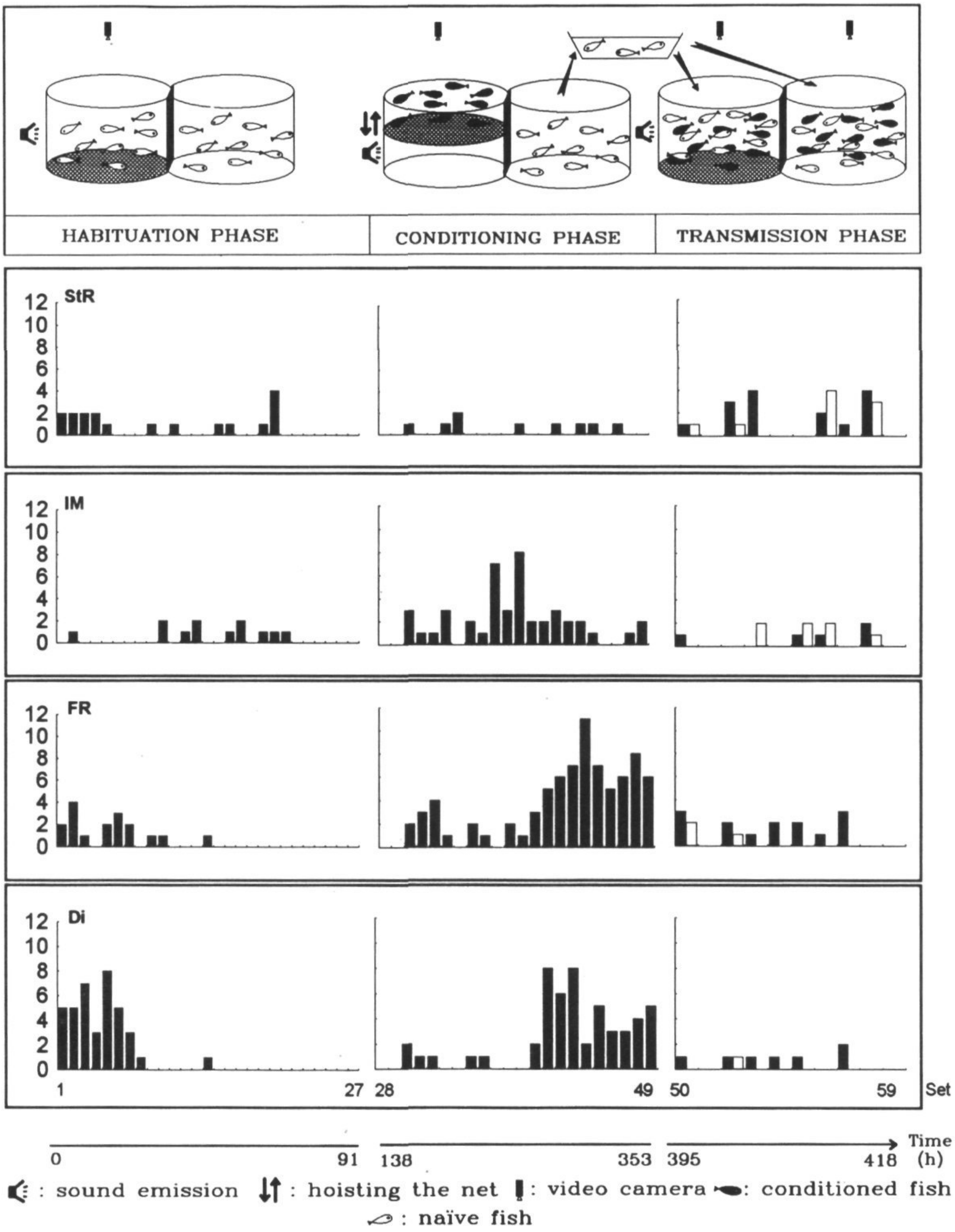

Figure 1. Three phases of the experiment (upper part) and results (lower part) expressed as frequency histograms of reactions to the conditioned stimuli in the tank with net (black bars) and in the other tank (white bars): startle response (StR), imperfect mill (IM), flight reaction (FR), dislocation (Di). Set refers to sets of three sound pulses (see text).

times. The reactions of the two mixed schools of conditioned and naïve fish, present in the same proportion in each tank (18/18 in tank WN; 17/17 in tank B), were compared.

During these three phases, each test was recorded on videotape. The fish in the tanks were swimming slowly in a circle, forming a typical mill structure (which is known as a good index of stability and quiet behaviour of a school) which they maintained as long as they were not disturbed. The reactions of the school were measured through four behavioural criteria which are, in order of increasing excitation: (1) startle response (StR), which affects one fish and does not lead to reactions of the others; (2) imperfect mill (IM), a contraction of the mill structure with a disruption of the regular swimming; (3) flight reaction (FR), which could be with fast regrouping, or dispersion; and (4) dislocation (Di), characterized by fast and erratic swimming that disorganized the school.

Results

As no mortality and no unexpected behaviour occurred during the experiment, we considered the fish to be correctly adapted to captivity. During the habituation phase, the strong responses (Di, FR) decreased in intensity and vanished rapidly after the first six sets (Fig. 1, left), which means that the sound pulses no longer elicited any fish reaction.

During the conditioning phase, the fish started to react after the third set of CS, and the reaction was well established after a dozen sets. A progressive change in behavioural response from StR to Di occurred (Fig. 1, middle). Nevertheless the conditioned reactions never became as strong as the panic observed during the hoisting of the net.

During the transmission phase, limited reactions of the mixed school in tank B were noted: after 3 series of sound pulses, some StR and IM appeared but stronger reactions were never displayed except one Di and three FR during the three first sets. By contrast, in tank WN we observed FR and Di at the beginning of the stimuli sequence. These reactions declined quickly and became individual StR in the end. We did not observe progressive extinction from Di to StR. No responses were noted after the 9th set (Fig. 1, right).

Discussion

These results show that conditioning of "primitive" fish such as clupeoids is possible. Several authors have shown that avoidance by fish or other animals of aversive conditions or predators could be reinforced by learning (Gleitman and Rozin, 1971). Conditioning by an attractive UCS such as food is well known in aquaculture (e.g. Suboski and Templeton, 1989). Concerning the conditioning process, the increasing responses from StR to Di can be explained by individual differences in ability to learn (Pyanov, 1993) and/or by mimicry or a social facilitation process (Helfman and Schultz, 1984).

Concerning the transmission phase, the strongest reactions (FR and Di) were displayed in tank WN. As they concern the whole school they give evidence for conditioned fish leading the "naïve" ones. In the case of IM and StR behaviours, we assume that they were performed by conditioned fish which disturbed to some extent the "naïve" fish but did not lead them. These reactions occurred essentially in tank B. These differences between the two tanks could result from participation of the net used as the aversion stimulus still being present lying on the bottom of the tank WN. Catching sight of the net should be associated with hoisting, and therefore a part of the UCS was maintained in tank WN during the extinction phase. This result shows that a conditioned response cannot be dissociated from the context in which it is expressed (Jenkins, 1984).

In order to relate the results to *in situ* fishing conditions, we have to compare the number of necessary CS repetitions with the number of successful escapes and survivals of fish from a gear. This last point has only recently been documented (see other contributions to this volume) but it does not seem unrealistic to expect that some fish could have the opportunity to learn. If not, fish will probably die before learning, except if a stronger stress could reduce the learning time ("one-trial learning").

We have shown that naïve fish could respond appropriately to the reactions of the trained fish despite knowing nothing of their particular learned experience. Opportunities for experienced fish leading the inexperienced probably exist in natural conditions (fishing grounds), and owing to the low degree of fidelity of individuals to a school (Helfman, 1984), these kinds of mixed schools should exist. Therefore, catchability in heavily exploited stocks could be lower than that in unexploited stocks.

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The behaviour of cod around a cod trap as observed by an underwater camera and a scanning sonar

Pingguo He

He, P. 1993. The behaviour of cod around a cod trap as observed by an underwater camera and a scanning sonar. – ICES mar. Sci. Symp., 196: 21–25.

The behaviour of the Atlantic cod (*Gadus morhua* L.) around a modified Newfoundland cod trap was monitored using an underwater video camera and scanning sonar. Cod were observed to swim into the trap and exit the trap at both entrances. The maximum entering rate was 733 fish/min, and the maximum exiting rate was 130 fish/min. Swimming speeds, swimming depths, and tracks of moving schools around the leader and at the entrances of the trap were analysed from video and sonar recordings.

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Introduction

The cod trap is the main fishing gear in the Newfoundland inshore fishery. The traditional Newfoundland cod trap is one of the simplest fish traps and has been used by Newfoundlanders for more than 120 years. In the 1960s, several versions of Japanese traps were introduced from northern Japan, where they were used for catching the Pacific cod. The modified Newfoundland trap is a combination of the traditional Newfoundland trap and the Japanese traps. The cod trap is an efficient fishing gear for catching migrating fish: one trap can catch as much as 10 tonnes of cod in 24 h and a crew of five can operate as many as eight traps. Cod traps vary in sizes, depths and rigging to suit local fishing ground conditions.

The cod trap is a passive fishing gear, set on a fishing ground to intercept migrating schools. Therefore an understanding of fish behaviour and fishing ground conditions is very important. Studies of cod traps in Newfoundland include those of Bishop (1982) on mesh selection and Lear *et al.* (1986) on the influence of environmental conditions on the catch. Although efforts have been made to record the shape of cod traps under fishing conditions by using either divers or remotely controlled vehicles, the behaviour of cod around Newfoundland traps has not been investigated. In contrast, numerous studies have been carried out in Japan investigating fishing mechanisms of trap fishing and fish behaviour around traps (e.g. Nomura, 1980; Inoue and Arimoto, 1987; Inoue, 1988). Traps used in Japan (called set-nets) are more complex in design, larger in size, and catch a greater variety of fish species than those used in Newfoundland.

To compare fishing efficiency and selectivity of different commercial cod traps and to develop more selective cod traps, the Marine Institute initiated a programme including model tests in a flume tank and field observations of cod behaviour in and around traps. This paper reports underwater observations of cod behaviour near a modified Newfoundland trap during July–August 1990.

Materials and methods

Underwater observations were conducted at a depth of 26 m in Logy Bay (47°37′35″N 52°39′55″W) near St John's, Newfoundland (Fig. 1). The bay has a northeasterly aspect and opens into the Atlantic Ocean. Therefore, northeasterly winds cause rough surface and strong ground swells, while southwesterly winds result in calm water. Rocky bottom dominates the seabed at depths less than 30 m.

The fishing gear under observation was a modified Newfoundland trap with winker panels at the entrances (Fig. 2). It was owned and operated by a commercial fisherman of St John's. The trap body was 110 m (60 fms) around the perimeter, 22 m (12 fms) deep, set in a water depth of 26 m (14 fms). The mesh size was

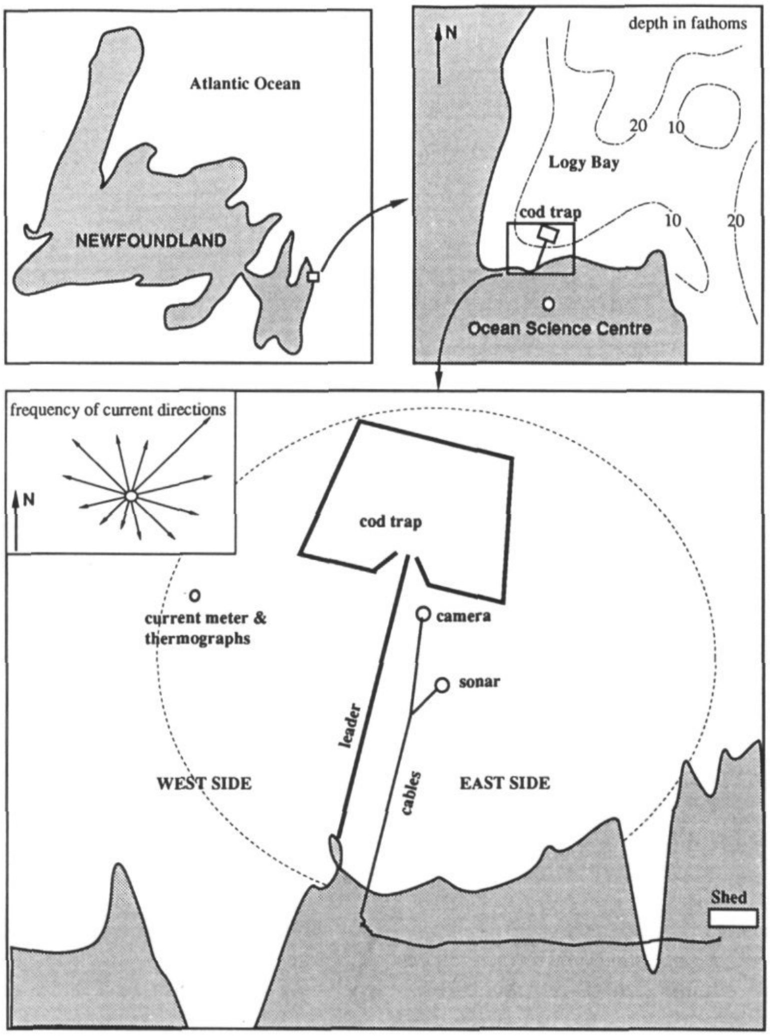

Figure 1. Schematic drawing showing the positions of the scanning sonar and video camera installed near a modified Newfoundland cod trap in Logy Bay on the east coast of Newfoundland. Two cables linked the underwater equipment and the control and recording devices in the shed. The inset shows the frequency of current directions (arrows), in 30° sectors, as measured by the current meter; the longer the arrow, the more frequent is the current in that direction. The dashed circle indicates a sonar range of 70 m. Drawing not to scale except the inset of current directions.

203 mm (8″) in the leader and 92 mm (3⅝″) in the "drying twine"; all other netting had 127 mm (5″) mesh. The leader was 104 m (57 fms) long and set with a compass heading of 200° (true north) towards the shore.

The experimental setup for cod behaviour observations is sketched in Figure 1. An underwater video camera (Osprey OE1301, Osprey Subsea, California, USA) was installed 4 m from the east entrance on the seabed. A scanning sonar transducer (Fish Scanner type 411, American Pioneer, Seattle, USA) was installed on the bottom 30 m from the same entrance and 15 m from the leader. Two underwater cables for the camera and the sonar ran along a mooring rope towards the shore and into a shore-based observation shed. The mooring, cables and all other equipment and devices were completely separated from the trap, which was fished on a daily basis. The underwater video was recorded on a video cassette recorder through a timer. The sector-scanning sonar operated at a frequency of 160 kHz. The colour display of the scanning sonar image was recorded by a second video camera (Panasonic D5000, Japan). Continuous observation of cod behaviour near the trap was made from 00.50 to 21.00 h. Observations lasted for 11 days between 26 July and 5 August 1990. A total of 130 h of underwater video recording and another 78 h of sonar recordings were made.

A self-recording current meter (Aanderaa RCM – 4/5) measuring current velocity, direction as well as water temperature was moored at 5 m off the bottom, 50 m from the trap and 25 m deep. Two additional

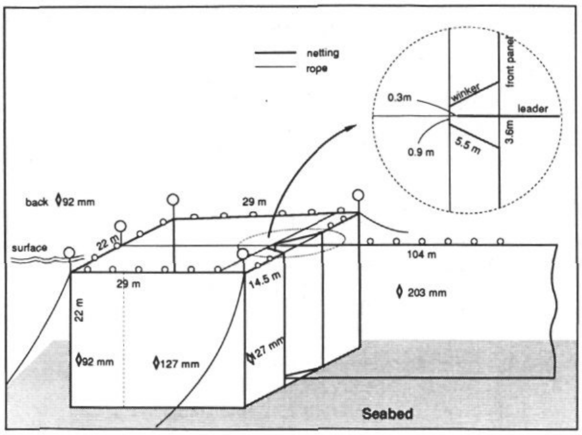

Figure 2. Schematic three-dimensional drawing of the modified Newfoundland cod trap. The trap was set at water depths of 26 m, with the leader towards the shore (Fig. 1). The length of the leader was 104 m. Drawing not to scale.

thermographs were used to monitor water temperature in midwater (10 m below surface) and 2 m below the surface. Both the current meter and the thermographs recorded data at 15 min intervals.

Video recordings were analysed to determine the swimming speed of cod entering the entrances, leaving the entrances, inside the trap, outside the trap during hauling, and when being startled. Speed was calculated by the distance a fish swam (on the video screen) in a time period by the length of the fish on the screen, giving a relative value of body lengths per second ($L\,s^{-1}$). The tailbeat frequency of fish was counted and expressed as the number of beats in one second (Hz).

The number of fish swimming in and out of the trap entrances was counted from the video screen. Distinct cod schools were traced from sonar recordings to illustrate the movement of the school in and out of the trap and along the leader in a given time period.

Results

The swimming speed of cod entering and leaving the trap was very low. Samples of swimming speed measurements showed an average of less than $1\ L\,s^{-1}$ at water temperature from 1.6 to 12.9°C. However, the swimming speed of a startled school was measured at around $4\ L\,s^{-1}$ (Table 1).

Table 1. Swimming speeds of cod (*Gadus morhua* L.) measured from video film made near a modified Newfoundland trap.

When	Swimming speed ($L\,s^{-1}$)	Tail beat frequency (Hz)	No. of samples
entering trap	0.8	1.4	9
leaving trap	0.7	—	5
inside trap	0.6	—	10
under trap	1.1	1.9	5
being startled	3.9	—	2

The swimming depth of cod depended on the magnitude of the ground swell in the area, which was related to the direction and strength of winds. The stronger the ground swell (easterly winds), the higher the fish rose off the bottom, and conversely. In exceptional calm days with light southwesterly winds, fish swam only 0.5 m off the bottom and stayed at the entrance for as long as 10 min. In rough days with strong easterly or northeasterly winds of 30 km h^{-1} or more, fish swam more than 10 to 15 m off the seabed. The direction of current was influenced by the ground swell as well. As a result, no prevailing current directions were recorded at the position of the current meter (see Fig. 1).

Cod swam into the trap from both the east and the west entrance. Likewise, they also swam out through both entrances. There are a number of examples indicating that a group of cod swam into the trap from one entrance and a portion of it exited the other entrance (Fig. 3). During most of the day, cod appeared at the entrance in small numbers; only very occasionally did large schools swim into or out of the trap. On one

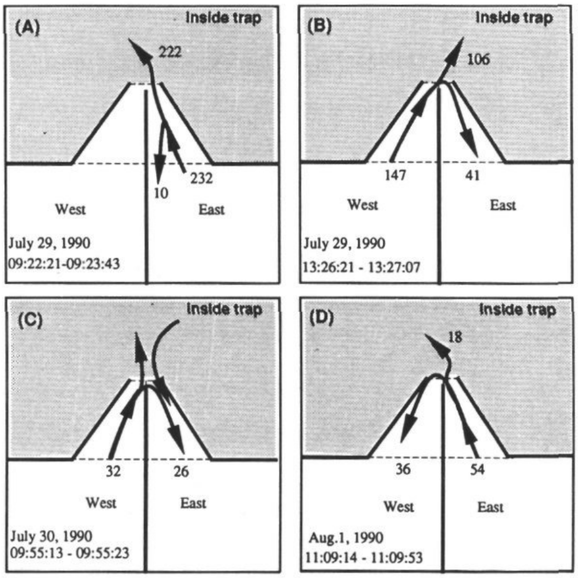

Figure 3. Examples of cod swimming into and out of the modified Newfoundland cod trap as observed by an underwater video camera stationed on the seabed near the east entrance. The time on each graph indicates the period during which the fish number counts were made. (A) 10 out of 232 cod hesitated at the east entrance and swam back out; (B) 147 cod swam into the west entrance, while 41 of them swam out of the east entrance; (C) 32 cod swam into the west entrance, while at the same time, some fish swam out of the trap and a total of 26 cod swam out of the east entrance; and (D) 54 cod swam into the east entrance, while at the same time, 36 of them swam out of the west entrance.

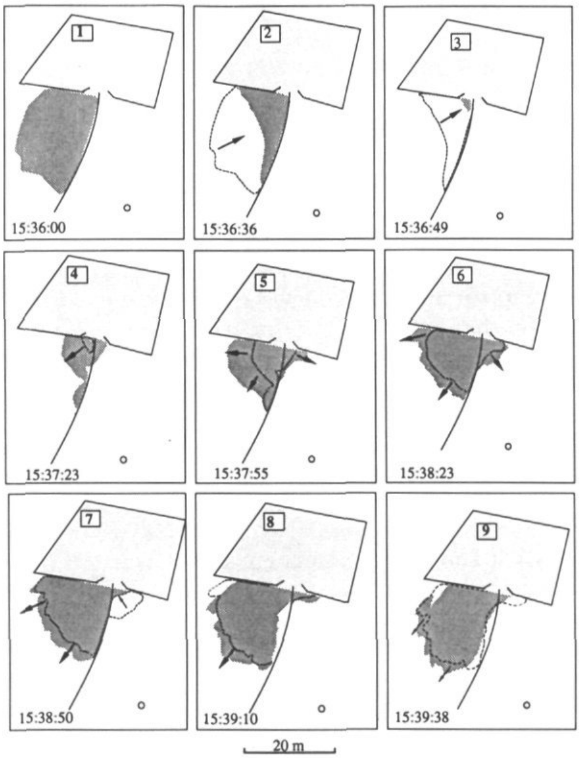

Figure 4. Movement of a cod school in and out of the modified Newfoundland cod trap on 2 August 1990 as observed by a scanning sonar. The dark-shaded area denotes the school outside the trap at the time indicated. Dashed lines indicate previous positions of the school and arrows indicate the direction of movement. Scale 20 m horizontal distance. The position of the sonar is indicated by open circles. Nos. 1 to 9 indicate the sequence. Notice that the school swam into the trap and roughly the same number swam out of the trap in three and half minutes.

occasion, a school of 1100 cod was observed by the video camera to swim into the trap from the west entrance in 1.5 min, representing an entering rate of 733 fish $\min^{-1}$. On another occasion, a school of about 325 cod swam out of the trap from the east entrance within 2.5 min (exiting rate of 130 fish $\min^{-1}$). On a third occasion, a large cod school swam into the trap and almost the same number of fish (similar area on sonar display) swam out of the trap in 3.6 min (Fig. 4). Inside the trap, cod appeared to swim along the perimeter of the trap in both clockwise and counter-clockwise directions.

During the entire period of observation by the camera, only one cod was observed to swim through the meshes of the leader and the front panels, even though these meshes are large enough for cod to swim through. However, when panicked during hauling, a large number of small fish appeared to have swum out of the small-mesh (92 mm) “drying twine”.

The leader of the trap was observed to guide fish both away from and towards the entrances (Fig. 5).

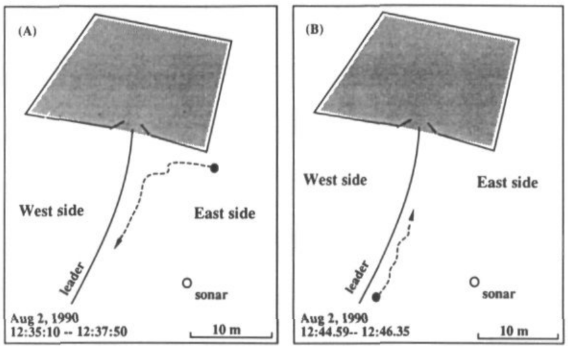

Figure 5. Movements of cod schools near the modified Newfoundland trap as observed by a scanning sonar. (A) A school approached from the east side front corner and was guided away from the entrance. (B) A school was spotted near the shore and guided along the leader towards the entrance of the trap. The dashed line indicates the track and the arrow denotes the direction of movements.

Discussion

Inoue (1988) used a scanning sonar to survey several trap (set-net) fishing grounds and various types of traps. He was able to identify the movement of fish schools in relation to time of day, depth contour, and position of the leader and main net. However, using only sonar equipment it is difficult to determine individual fish movements within a dense school. The present series of observations combined far-field sonar observation and near-field video observation to monitor movements of fish schools as well as of individual fish. To avoid human influence on fish behaviour around the cod trap, natural light only was used for the camera instead of artificial lights. There was sufficient sunlight for the camera to operate from dawn to dusk. The camera and the sonar transducer were stationed on the seabed, instead of being operated by divers or underwater vehicles, to reduce their influence on cod behaviour. All the observation equipment and devices were separated from the fishing gear, so that the shape of the trap was not altered by the equipment and commercial fishing operations were not interrupted.

The video camera proved very important in monitoring fish movements at the entrances, because the netting panels forming the winkers tended to obscure the sonar image. Though counting the number of fish on a video screen was not easy, it was possible to analyse the rates of entrance and exit in a comparative manner. The large number of cod swimming out of either entrance, as observed both by the video camera and by the sonar, indicates that the entrances need to be modified to avoid escapement. A funnel arrangement such as that in the Japanese-style traps would probably help prevent the large-scale exodus of fish.

The swimming speed of cod on the fishing ground of $0.8\ \mathrm{L\ s^{-1}}$ is less than the maximum sustained swimming speed of cod measured under laboratory conditions (He, 1992). This indicates that these fish can swim at these speeds indefinitely without leading to exhaustion. However, a speed of 4 L s^{-1} when being startled will lead to exhaustion within minutes. The maximum current on the fishing ground was 0.25 m s^{-1}, equivalent to 0.5 L s^{-1} for cod of 0.5 m length. Adult cod can outswim this current speed without leading to exhaustion, even at the lowest temperature of 1.6°C on the fishing ground.

The leader of the trap served well as a guiding barrier, though fish schools were observed to be guided towards or away from the trap entrances. The leader was constructed of dark material and encrusted with algae after being submerged for an extended period. In shallow water of less than 30 m in daytime, the netting of the leader gave a good contrast when viewed horizontally or upwards, and could be clearly seen at distance. Even though meshes in the leader were much larger than those of the gill net for the same fish size, video observations indicated that only one cod swam through the mesh in the leader during the entire observation period. There would probably be more cod swimming through large meshes at night, when the visibility of the netting becomes poorer at low light levels, but no observations have been made at night to support this assumption.

In contrast to the above phenomenon of cod not willing to swim through large meshes in normal fishing conditions, cod were eager to swim out of smaller meshes in the back of the trap during the hauling process. While this escape reaction might have resulted in size selection of the trap by allowing smaller fish to escape, a large number of medium-sized cod became meshed in the small-mesh back panel. Further studies are needed to design sorting devices to increase selectivity of the traps and to reduce entanglement in the nettings.

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Packing density structure of herring schools

Ole Arve Misund and Svein Floen

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The packing density structure of free-swimming herring schools when entering the hibernating areas in fjords in northern Norway has been studied using a "cell"-echo integration technique. The recordings revealed an internal variation in packing density by an order of 100, and regions of rather high density were detected in some of the schools. Repeated recording of the schools at intervals of 3–5 min showed that the schools maintained a certain packing density characteristic, even if substantial changes in packing structure were detected.

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Introduction

Fish schools are organized by individuals in synchronized and polarized motion (Pitcher, 1983). This creates the impression of schools as compact structures with equally spaced individuals, all performing similarly as in a single, egalitarian unit (Radakov, 1973). Breder (1976) speculated that such a uniform structure was accomplished if the individuals packed in a complicated geometric structure which he argued resembles a rhombic lattice. Pitcher (1973) asserted that optimal packing (maximum number of equidistant neighbours) will be obtained in a tetradecahedronal pattern, and he observed that schooling minnows tend to pack in a suboptimal tetrahedronal pattern.

Detailed quantification of the three-dimensional positioning of individuals in schools revealed, however, a rather dynamic structure (Partridge *et al.*, 1990). The distance between individuals varies considerably, and is dependent upon the relative spatial positions among neighbouring individuals. The packing structure is therefore not fixed, as the spatial positions among neighbours also vary. Nevertheless, there are tendencies to a certain spatial structure within schools, originating from preferences for spatial angles and distances to companions (Partridge *et al.*, 1990).

Differences in behaviour among individuals also create substantial dynamics within schools. Individuals change positions and swimming speed, even within schools moving at constant speed and heading (Partridge, 1981). The synchrony is maintained, however, because individuals match changes in swimming speed of their neighbours at time lags of about 0.2 s (Hunter, 1969).

Formation of subgroups can create an even greater dynamic within schools. Such groups can be quite stable over time, and members of one subgroup show strong correlations to members of the same group, but low or negative correlations to members of other groups (Partridge, 1981). For the school to exist as a unit, however, the movements of adjacent subgroups must be linked, even if they are not quite synchronous (Pitcher, 1973).

In agreement with the variability in school structure detected in small-scale experiments, quantification of the packing density of clupeoid schools by detailed echo integration revealed that substantial variation is present in the internal structure of free-swimming schools (Gerlotto and Freon, 1988; Misund, 1990a). This variation is reduced when schools react by packing more densely if passed over by a survey vessel or exposed to predators (Freon *et al.*, 1992). This response indicates that the packing structure of schools is rather labile, and therefore great variations may be expected from one recording of a school to another. This expectation implies that biomass estimation of schools based on geometric measurements by sonar and subsequent conversion by school area or school volume-to-school biomass relationships (Misund *et al.*, 1990) will be rather unreliable.

To study the change in packing structure of herring schools within a limited time scale, recordings by a "cell"-echo integration technique were conducted when the herring entered a fjord area in northern Norway for hibernation. The results are discussed in relation to the possibilities of biomass estimation of schools using multibeam sonar.

Materials and methods

The herring schools were recorded by RV "Fjordfangst" (20 GRT) when they entered the hibernating area in the fjords around Harstad, northern Norway, in late September/early October 1990. The vessel was equipped with a FURUNO CH-12 multibeam sonar (150 kHz) and a SIMRAD EY 200 echo sounder (38 kHz) connected to a PC-based echo integrator (Floen *et al.*, 1991). The echo integration unit was calibrated according to standard procedure (Foote *et al.*, 1987).

The herring schools were located by the sonar, and the vessel passed over them once so the echo sounder could record swimming depth and vertical extent. The schools occurred between about 10 m and about 60 m depth. Before a "cell"-integration transect, the PC-integrator was set to produce printouts at intervals of three echo sounder pings for 15 pelagic channels, each set with a vertical range of 3 m. The first layer was set at a depth just above the top of the school, and all schools were recorded within the 42 m depth interval of the other 14 pelagic depth channels. The echo sounder operated with a pulse length of 1 ms and a bottom-depth-dependent pulse repetition rate that produced about 90 pulses min^{-1} at the bottom depth (about 100 m) where most of the schools were recorded. The threshold of the echo integrator was set to 10 mV. The vessel was manoeuvred at a speed of $2.6\,\text{m}\,\text{s}^{-1}$ (5 knots), and the "cell"-integration was started shortly before the school was recorded on the echo sounder, and stopped as soon as the school was transected. The recorded echo integration values were then stored on a separate file, and the PC-integrator was cleared for another transect. Twenty-eight schools were transected at least twice, and 14 of the schools were transected three times. The time interval between transects varied from approximately 3 to 5 min, and each transect was laid at a different direction through the school.

Four schools were caught by purse seine, and subsamples of about 100 specimens from each catch were taken for measurement of length to the nearest 0.5 cm. The target strength of the herring (34.1 cm on average) was calculated by $TS_{\text{clupeoid}} = 20 \log L - 71.9$ (Foote, 1987), and the fish density of the integration "cells" was estimated as outlined by Misund (1990a). The recordings were filtered with a lower limit of fish density equal to 0.1 herring m^{-3} (Misund, 1990a) to reduce the influence of marginal recordings.

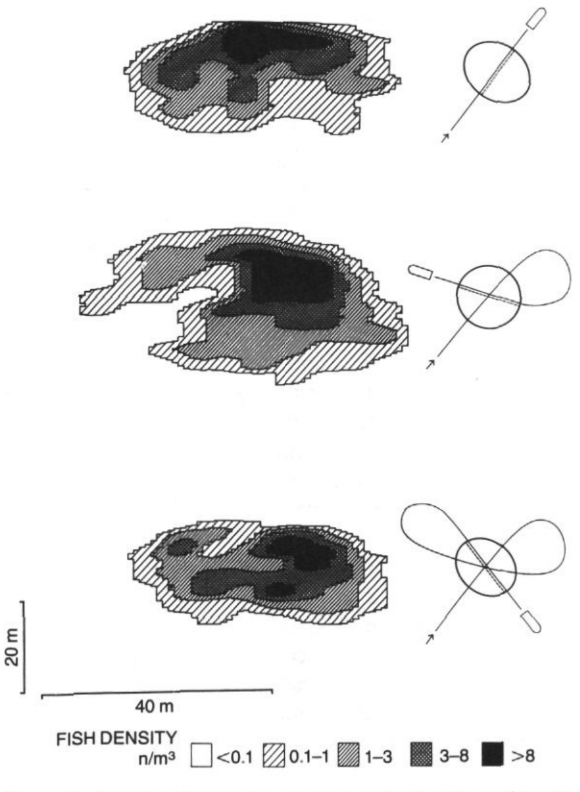

Figure 1. Packing density structure in vertical sections through a herring school quantified for three different transects at time intervals of 3–5 min. Sketches (plan view) at right indicate order and direction of transects.

Results

The cell integration revealed large variations in packing density within the herring schools (Figs. 1, 2). In several schools, regions of rather high density appeared (Fig. 1), and in the largest schools several such regions were detected (Fig. 2). The school surface was not even, but rather deflected by inward and outward bends.

Repeated "cell"-integration at time intervals of about 3 to 5 min indicated that the schools seemed to maintain distinct internal packing density structures (Figs. 1, 2). Accordingly, the schools were recorded with about the same maximum or average packing density in two or even three succeeding integration runs (Figs. 3, 4). There was a substantial variation in packing density among the schools, however, ranging from about 0.3 to 5.0 herring m^{-3} on average. Similarly, maximum packing density among schools ranged from about 0.8 to 27.0 herring m^{-3}.

Discussion

As found by Gerlotto and Freon (1988), Freon *et al.* (1992), and Misund (1990a), there was a variation by about 100-fold in the packing density within different regions of the herring schools. Is this great variation real

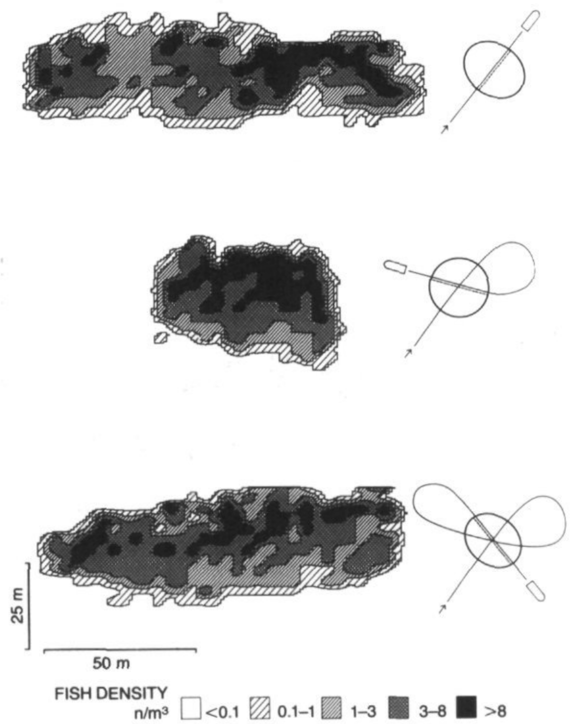

Figure 2. Packing density structure in vertical sections through a large herring school quantified for three different transects at time intervals of 3–5 min.

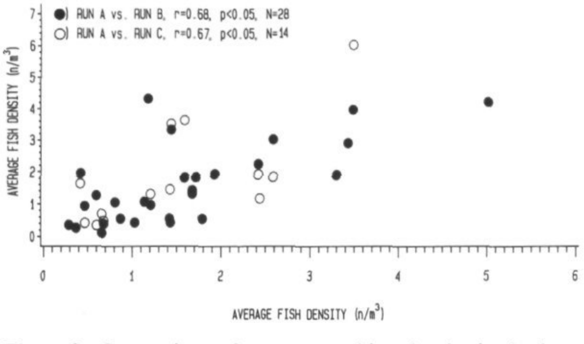

Figure 3. Comparison of average packing density in the herring schools for the first (A) and second (B), and first (A) and third (C) transect, respectively.

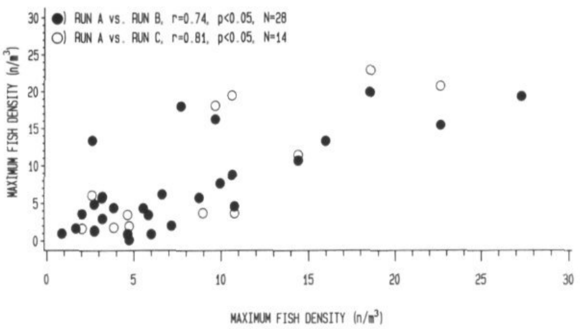

Figure 4. Comparison of maximum packing density in the herring schools recorded in the first (A) and second (B), and first (A) and third (C) transect, respectively.

or just an artefact caused by the acoustic method? According to the linearity principle of fisheries acoustics (Foote, 1983), it is necessary with a large number (in the order of several hundred) of pings for the mean backscattered echo energy from a single scatterer to stabilize. If a large number of scatterers is insonified simultaneously, as is the case with schools, the mean backscattered echo energy will stabilize after a much lower number of pings. But whether only three pings, as used in this study, are sufficient to obtain a backscattered echo energy that represents the true fish density in the different "cells" of the schools, remains to be answered.

However, the packing density recordings are probably reliable, as the interfish distance in the densest parts of the schools was quantified to about 1 body length (equal to about 27 fish m^{-3} of 34-cm long herring, assuming cubic packing). Such density is approximately the same as has been observed for herring when schooling in an artificial environment in an aquarium (Pitcher and Partridge, 1979). The average density (about 1.6 fish m^{-3}) of the free-swimming herring schools indicates a much looser packing at an interfish distance of about 2.5 body lengths. As this average value is computed from a large number of pings on many schools, it is likely to be quite close to the true mean according to the linearity theorem of fisheries acoustics (Foote, 1983).

Owing to the beam geometry, there is a substantial overlap between succeeding pings of the echo sounder. This implies that there is also a certain overlap between the volume covered of succeeding integration "cells" in the horizontal direction. However, the herring schools were obviously moving during the recordings, so that succeeding "cell" recordings were more or less independent. This independence indicates that the variation in packing density within the schools is probably valid.

The recordings of Freon *et al.* (1992) show that schools organized a more even and denser internal packing structure when reacting to a survey vessel that passed over them. As it is a common reaction of schooling individuals to close ranks when exposed to threats (Pitcher, 1986), this also indicates that the acoustic method reflects the reality of packing density distribution within schools.

Misund (1990a) proposed that the great variations in internal packing density are caused by differences in swimming speed and level of arousal within schools. Such variations result in the "dynamics of moving masses" phenomenon, which probably will be especially apparent when free-swimming schools change direction, react to predators, or come across patches of food. By analysing the Doppler shift in reflections from free-swimming schools, Holliday (1977) has shown that such internal speed variations exist even within schools moving at seemingly constant speed and direction. As speed increases, the individuals swim more closely (Partridge *et al.*, 1990), and the packing density (which is proportional to the cube of the interfish distance) may increase substantially.

However, owing to the geometry of the sound beam, the mapping of the packing density structure along the school edges will not be quite accurate. This is because the first and last "cell" element in each layer of a school recording will be substantially influenced by marginal recordings. Filtering the recordings by a threshold density equal to the median in the uncorrected density distribution for these "cell" elements (Misund, 1990a) will "sharpen" the recordings of the school edges to a limited extent only.

Despite the large internal variations, there was also a substantial variation in packing density structure among the schools. In addition to differences in swimming speed and level of arousal (Pitcher and Partridge, 1979), this can also be the result of different hunger level (Morgan, 1988; Robinson and Pitcher, 1989), or exposure to predators (Pitcher, 1986). Similarly, the observation that the herring schools seemed to maintain a certain packing density characteristic for time intervals up to about 10 min was probably an effect of these factors. Hungry individuals that are organized in a loosely packed school are unlikely to feed in such a short time, and frightened individuals that have become densely packed will not organize a more loosely packed unit immediately after a threat. Misund (1990b) has also shown that average swimming speed can vary substantially among herring schools, but that the initial swimming speed remains fairly constant for time intervals up to 25 min.

School biomass estimation based on measurements of school dimensions by multibeam sonar as suggested by Misund *et al.* (1990) requires that there be a certain stability in school structure. Considering the large internal variations in packing density, schools seem to organize rather labile structures. However, this study shows that herring schools maintain a certain packing density structure for time intervals up to 10 min, but also confirms that there can be substantial variations among schools.

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Variability of *Harengula* spp. school reactions to boats or predators in shallow water

Pierre Fréon, François Gerlotto, and Marc Soria

Fréon, P., Gerlotto, F., and Soria, M. 1993. Variability of *Harengula* spp. school reactions to boats or predators in shallow water. – ICES mar. Sci. Symp., 196: 30–35.

The internal structure and behaviour of clupeid schools has been observed *in situ* during unstressed periods followed either by natural predation or by applying a controlled stress (a realistically painted model predator). Combined acoustic and visual (aerial and underwater) observation techniques were used. *In situ* observations are characterized by a high variability of fish reactions in space and time. The variability in space is obviously due to the large scale of observation which allows the simultaneous occurrence of different types of behaviour in different regions. The variability in time is probably due to a large number of physiological or environmental influences changing unexpectedly between repeated experiments. The variability of fish reaction depends on the characteristics of the source of the stimuli: some sources (e.g. predators) induce different behavioural patterns according to the number of stimuli; others (e.g. boats) induce a single pattern, varying only in intensity. Consequences for acoustic signal identification are discussed.

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Introduction

A fish school is often considered as a body with a constant external ovoid shape, whose members are polarized and swim in a concerted way with coherence, cohesion, and homogeneity. Most observations on school behaviour are performed in aquaria, tanks or other restricted areas, limiting the number of biological or environmental influences governing the characteristics of a school (Radakov, 1973; Breder, 1976; Pitcher and Partridge, 1979). In these conditions, variability in school structure and reactions to stimuli might be restricted.

In this paper we report *in situ* experiments, to investigate whether the large number of fish and the probably higher number of influences generate the same kind of reactions, with the same level of variability, as are observed in aquaria etc. We focused our attention on changes in structure and behaviour of tropical pelagic schools subjected to two sources of external stimuli: predator and vessel. This information is of interest in the case of acoustic surveys, as recent research programmes intend to use school characteristics for species identification (Rose and Leggett, 1988; Souid, 1989) or biomass estimation (Misund *et al.*, 1990).

Material and methods

The experiments were carried out in a small bay (2 km diameter) in Martinique, French Caribbean, and were performed on *Harengula clupeola*. This species is a small, coastal clupeoid (12 cm fork length) forming schools usually smaller than two tonnes, i.e. approximately 10^5 individuals. The methodological approach involved *in situ* observations and combined visual and acoustic techniques.

Acoustic data were obtained from a Simrad EY-M portable echo sounder (70 kHz) connected to a wide-beam transducer (22° at the −3 dB point), and were recorded on a portable digital audio tape (DAT) recorder. The equipment was powered by a 12-volt battery. In the laboratory the signal was post-processed by paired transmissions using a digital echo integrator set with narrow depth intervals of integration (1 m or 1.4 m). The acoustic records were kriged and mapped using smoothing software (SURFER). Two kinds of visual observation were recorded simultaneously during several one-hour surveys: underwater views recorded by a swimmer and aerial photos from an ultra-light aircraft flying at an altitude of 60 to 90 m. A Handicam video camera (24° lens) and a Nikonos V camera (28° lens) were used underwater and a reflex camera (100–200 mm zoom and polarizing filter) was used onboard the airplane; 400 ASA film was used in both still cameras. The aerial photos were used to estimate the school surface (the boat length served as a scale). They also show variation of opacity in each part of the school, with some dark spots being easy to follow from one view to the next. Movement of these dark regions, associated with the swimming behaviour recorded by the underwater video, can give a good idea of the displacement of fish within the school.

The dinghy, with the echo sounder on board, towed a model predator (a realistically painted, 60 cm long, model of a bonito moulded in fibreglass from a fresh specimen of *Auxis thazard*) at the end of a 50 m nylon line and passed over the same school several times in shallow water (between five and eight metres). From eighteen operations carried out on one day we obtained eight successful sets of observation on the same school, with simultaneous aerial, acoustic and underwater recordings. These observations were compared with those performed one day later, when we were able to record chase and attack by three predators (*Euthynnus* spp.).

Results

The horizontal shapes (i.e. plan views) of the presumably unstressed schools and their surfaces are highly variable in time, as observed by other authors in different areas (Bolster, 1958; Squire, 1978; Hara, 1985). Before the boat crossed them, the schools looked slack and unstructured and their outlines were blurred. The simultaneous underwater observations of internal structure show non-polarized groups of fish in some parts of the school. In other parts or at other instants, synchronized movements of polarized fish take place. Intermingled or parallel and regularly spaced columns of polarized fish may also shape large vacuoles (Fréon *et al.*, 1992).

The two aerial surveys retained for the description of stressed schools are typical of all the observations. They show high variability in response of the school in terms of structure and concentration. During the first transect, school shape did not change throughout the passage of the model predator. From the movements recorded by the swimmer we can assume that the two dark areas in Figure 1 A3 are fish swimming rapidly in opposite directions on each side of the path of the boat and model predator. This displacement is interpreted as a partial fountain effect. After three additional passes the model induced a reaction of all the school, which adopted a rather compact structure and fled the disturbed area (Table 1A, Fig. 1 A4–A6). During the last transect, the model passed near the periphery of the school and we noted a local compression of the disturbed area followed by compaction of the whole school without shifting (Fig. 1 A7–A9). During this transect, the change in shape and surface of the school (Table 1A) associated with underwater observations strongly suggested that the two dark areas are fish that flock rapidly together.

A systematic diving of the upper layer of schools upon the approach of the boat was displayed during all these experiments (including those not presented here). In contrast, different reaction intensities were displayed upon the impact of the model predator. When the model was in the middle of the water column, we observed typical fountain effects of the fish "visually concerned" (Pitcher and Wyche, 1983). When the model was towed close to the bottom, fish were often structured in layers and avoided it by displaying a dense wall reaction. Finally, all the fish may flee before it with successive waves of agitation which run over the whole school as a shiver.

The diving and fountain effects seen at the approach of the model predator did not induce noticeable instantaneous modification of the horizontal shape of the whole school. Nevertheless, repetition of the stress was likely to induce such modifications. Instead of an expected habituation effect to false alarms, deformations and decreases of the surface were observed. Analysis of the acoustic signal revealed a corresponding increase in internal mean density and homogeneity depending upon the stress intensity, as shown in Figures 2 A1, 2 A2, 2 A3 and in Table 1 A, although these values should also be related to the location of the transect.

During the following day we observed the reactions of another school suffering chases and attacks from live predators (*Euthynnus* spp.). The aerial views showed first the progressive formation of an ovoid shape with sharp outlines, and high peripheral densities. Then the school split quickly into two homogeneous schools (Table 1B), the smallest of which fled the disturbed area and rapidly crossed the bay. The other, after a shorter drift, became compact and circular, and six minutes later split again into two other schools after briefly forming a "neck" (Fig. 1B) as described by Radakov (1973). The simultaneous underwater observations indicated that during predatory chases, the fish displayed several dense wall reactions and successive waves of agitation. When the predators attacked by breaking through the school like an arrow, the school became a compact ball. This compact ball with a high speed of reaction of the fish, and this splitting with a shift of the resulting schools, were never observed in response to the model predator. However, we obtained a similar compact structure after circling the school several times with the dinghy and model in a later experiment.

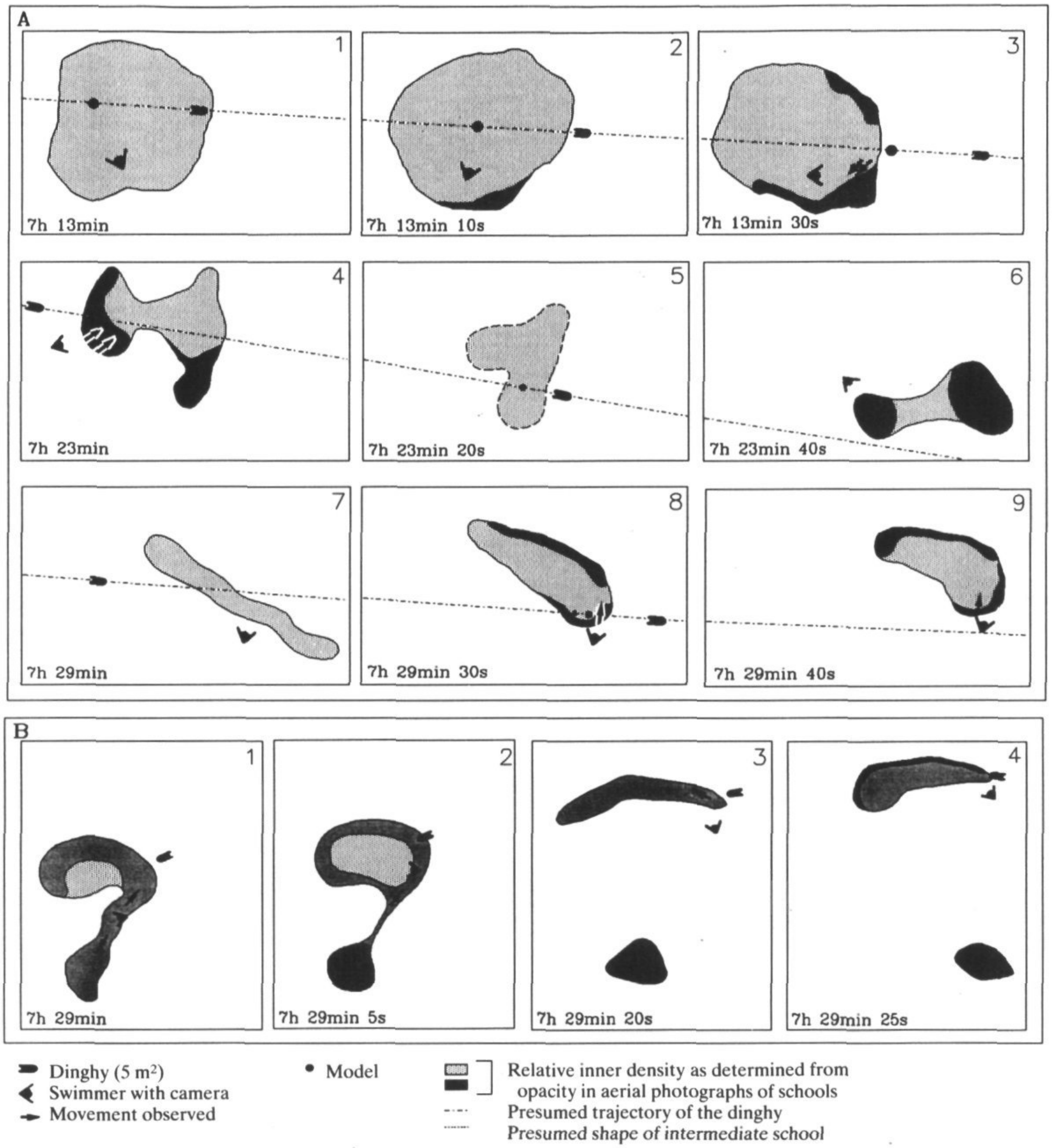

Figure 1. Two aerial observations of school reactions: (A) during three passes of the dinghy towing a model predator above the same school (5 June 1991); (B) during chases and attacks by predators (*Euthynnus* spp.) on a single school (6 June 1991). See also Figure 2.

Discussion

From these observations we can distinguish four types of behaviour: diving, fountain effect, dense wall reaction and waves of agitation. Diving and the fountain effect were always observed as local and instantaneous defensive behaviour. The first appeared just before the impact of the boat, and the second at the moment of visual contact with the model predator. The dense wall reaction and successive waves of agitation were also displayed locally upon visual contact with the model, but depending upon their intensity they may disturb a larger part of the school.

These four types of behaviour are local responses of fish within the school. We distinguish them from packing, splitting, and shifts of the whole school, which we name global reactions because they affect the whole social group. For instance, packing of the whole school into a spherical shape seems to result from several successive local compressions arising from the influence

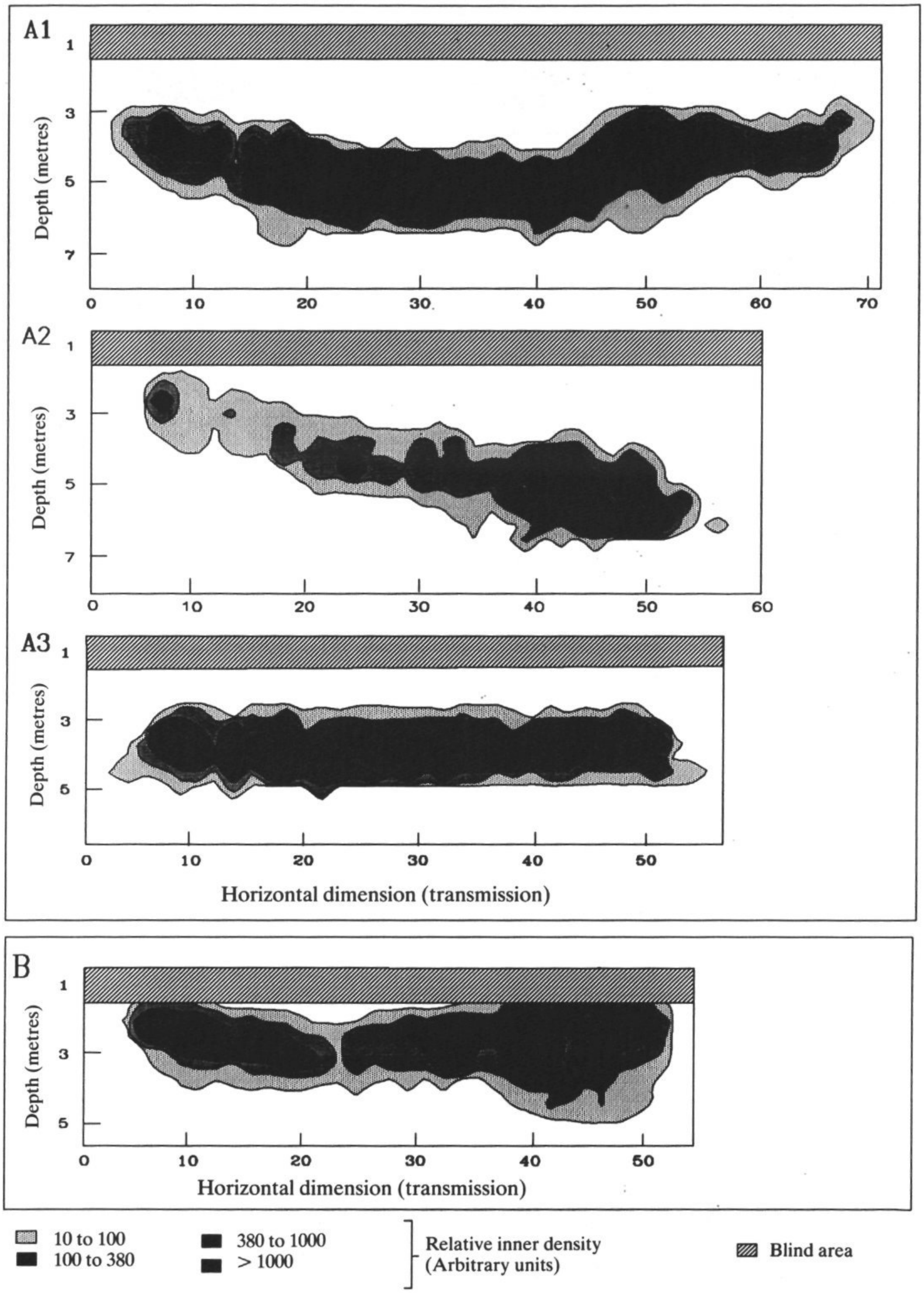

Figure 2. Internal density structure (acoustic vertical cross-sections) corresponding to Figure 1: (A) during three crosses of the dinghy towing a model predator above the school (5 June 1991); (B) during chases and attacks of predators (*Euthynnus* spp.) on a single school; drifting observations (6 June 1991).

Table 1. Data on school characteristics and reactions to different stresses (A) during crosses of the dinghy towing a model predator above the same school (5 June 1991), (B) during chase and attack of predators on a single school (6 June 1991).

A						
Crossing number	—	1	2	2	3	4
Figure 1, part	—	—	A.1	A.3	—	—
Time	7 h 07 min	7 h 10 min	7 h 13 min	7 h 13 min 30 s	7 h 16 min 50 s	7 h 22 min
Stress applied	None	Boat + model	Boat + model	Model	Boat + model	Boat + model
Density (a.u.)	—	—	1780	—	—	—
Height (m)	—	—	2–2.4	—	—	—
Depth (m)	—	—	4.5–5	—	—	—
Altitude (m)	—	—	1.8–2.2	—	—	—
Surface (m^2)	1300–1350	1160–1210	1100–1150	1100–1150	700–750	690–740
Circularity	2.3	3.3	1–1.1	1.1–1.3	2.2	6.3
Local reaction	None	Diving + Compressing	Diving + Compressing	Fountain	Wave agitation + Fountain	Compressing
Global reaction	None	None	None	None	Packing	Aborted split
Crossing number	5	5	5	6	6	6
Figure 1, part	A.4	A.5	A.6	A.7	A.8	A.9
Time	7 h 23 min	7 h 23 min 20 s	7 h 23 min 40 s	7 h 29 min	7 h 29 min 30 s	7 h 29 min 40 s
Stress applied	Boat approach	Boat	Boat + model	Boat approach	Boat	Boat + model
Density (a.u.)	—	710	—	—	5030	—
Height (m)	—	1.7–3.5	—	—	2.5	—
Depth (m)	—	2.0–7.0	—	—	3.5	—
Altitude (m)	—	6.0–1.0	—	—	0.5	—
Surface (m^2)	550–600	—	450–500	420–470	420–470	310–360
Circularity	5	—	3.6	10	2.6	2.0–2.1
Local reaction	Diving + Compressing	Compressing	Compressing	None	Diving + Compressing	Compressing
Global reaction	None	Packing	Packing	None	Packing	Packing
B						
Figure 1, part	—	—	—	B.1	B.4 (top)	B.4 (bottom)
Time	7 h 23 min	7 h 24 min	7 h 24 min	7 h 29 min	7 h 29 min 25 s	7 h 29 min 25 s
Stress applied	Predators	Predators	Predators	Predators	Predators	Predators
Density (a.u.)	—	1560	—	2345	—	—
Height (m)	—	3.0–4.0	—	4.0–4.5	—	—
Depth (m)	—	4	—	1.0–1.5	—	—
Altitude (m)	—	0.5–1	—	1.0–1.5	—	—
Surface (m^2)	630	330	90–100	350–400	170–180	60–70
Circularity	12.2	3.2	3	11	3.3	1.3
Local reaction	Mills	—	—	Fountain	Compressing	—
Global reaction	Splitting + Packing	Drifting + Packing	Drifting + Packing	Splitting	Drifting + Packing	Drifting + Packing

a.u.: arbitrary units. Circularity: ratio of length to width in plan view. Height: thickness of the school. Depth: distance of school from the sea surface. Altitude: distance of school from the seabed.

of visual contacts with predators in different parts of the school. But it cannot be an instantaneous phenomenon as observed in aquaria. The detailed behavioural mechanisms allowing reversibility between compact and slack internal school structure have been proposed by Misund (1990) under the "moving mass dynamic hypothesis" and by Fréon *et al.* (1992) under the names of "compressing/stretching and stretching/tearing hypothesis".

It seems important to distinguish the diving behaviour in front of the hull from the other behaviours. This behaviour, unlike the others, was systematically displayed upon the approach of the boat. The intensity of stimulus applied did not change the behavioural pattern. Other results, from experiments with a sailboat alternately using sails and engine, support this idea (Fréon *et al.*, 1990). Actually, it seems that the fish react to a very simple stimulus which could be: something in the upper strata which moves rapidly. Nevertheless, changes in intensity of the behavioural response may appear: higher speed, different tilt angle, longer time and therefore longer flight distance (Olsen *et al.*, 1983).

Possible limitations to the interpretation of our results were studied in the acoustic and visual observations (e.g. representativeness of a couple of transmissions as an independent sample, acoustic limitations, influence of the observer or of the aircraft's shadow) but their effects cannot be considered as the only explanation of the large variability observed in school packing density (Fréon *et al.*, 1992). Variability in response of fish in front of a model or living predators has been described by several authors (Radakov, 1973; Helfman, 1984; Pitcher, 1986;

Magurran and Girling, 1986), but as Pitcher says, "we do not clearly know what factors influence fish in deciding to perform one manoeuvre or another." From the basic behavioural studies (Tinbergen, 1971; Lorenz, 1973) it seems that the rule of heterogeneous stimuli summation can be applied to our results: the intensity of the response fluctuates according to the intensity, number and duration of stimuli.

First, the local and instantaneous responses of the fish in front of the towed model seem to change with its threat level. For instance, the reactions of fish become stronger with increasing towing depth. Because real predators chase close to the bottom in order to maintain and gather the school from the bottom to the surface before launching their attacks, the intensity of the stimulus "model swimming close to the bottom" might be stronger because it includes characteristics of the chase behaviour of predators.

Secondly, concerning the number of stimuli and their duration, our results show that the "global" responses of the school (packing, splitting and shift) are flight reactions induced by the association of several stimuli applied (or repeated) during a given time. We observed these global reactions during two circumstances. The first occurs in front of active predators. By their form, speed, number, colour and behaviour (such as cooperative chase and lateral threats) they induce several strong stimuli. For this reason probably, the local and instantaneous responses of fish are more strongly displayed towards predators than the towed model, which presents some but not all of the required alarm releasers. In the same way, the packing of the school and its division into two subgroups were observed when the boat passed overhead towing the model but, as mentioned earlier, these reactions were partial. For instance in three passes splitting into two schools was just initiated. The neck which was being formed became resorbed and the two groups of fish coalesced again. In most cases, compression was observed only in the disturbed area of the school. The second circumstance is when we towed the model predator while encircling the school with the boat: the effect of the model seemed emphasized and the school became strongly packed. The reason may be the circling "behaviour" of the model and/or that meanwhile the sight and sound of the motorboat is perceived by the school to come from all directions. These observations may be compared with those obtained by Gerlotto and Fréon (1990) on avoidance reactions of tropical fish to a survey vessel. They proposed a schematic classification of gradual reactions of fishes (alarm, flight and panic) as a function of cumulative factors such as noise, noise + light, noise + light + boat's hull.

Evidently a dinghy does not present the same intensity of emitted stimuli as a big research or fishing vessel, but the rule of heterogeneous stimuli summation could explain the relatively low lateral avoidance reactions of fish observed during acoustic surveys in our areas: whatever the strength of one or several stimuli, if some of them are missing, avoidance reactions will not be successfully completed. As a result, plans for improving acoustic survey estimates by incorporating school characteristics may suffer more from natural variability (especially related to predation) than from research vessel stress.

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Behaviour of Baltic herring in relation to a poundnet and the possibilities of extending the poundnet season

V. Tschernij, E. Lehtonen, and P. Suuronen

Tschernij, V., Lehtonen, E., and Suuronen, P. 1993. Behaviour of Baltic herring in relation to a poundnet and the possibilities of extending the poundnet season. – ICES mar. Sci. Symp., 196: 36–40.

A preliminary study was conducted to clarify the possibilities of extending the herring poundnet season into the autumn when herring stocks are dispersed along the feeding grounds. Water movements and the swimming patterns of Baltic herring (*Clupea harengus* L.) in relation to an experimental poundnet, placed in a typical poundnet fishery area in the Archipelago Sea (ICES Subdivision 29N), were monitored with a current meter, echo sounder, and gillnets. No schools were found in the bay. Scattered herring were swimming in the bay 3–4 m below the surface after dark. There was a dominant southwesterly water movement near the leader net and a higher fish density was recorded on the current side of the poundnet. Considerable numbers of herring were found to return from the leader net back in the direction from which they came. Problems in the capture process of a herring poundnet in autumn seem to be connected to the guiding performance of the leader net.

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Introduction

There are numerous, small variations in construction and rigging of trapnets used along the Baltic coast (Suuronen and Parmanne, 1984). The most pronounced difference lies in the type of bag net; the traditional trapnet has a hooped bag whereas the poundnet, a newer modification, has a large rectangular box as a bag. The trapnet season in Finland is restricted to the main spawning period of the Baltic herring (*Clupea harengus* L.). Trapnets are traditionally set along the migration routes and on the spawning grounds, usually in very shallow water. During the short season (May–June) the catch of a trapnet is generally 15–20 tonnes.

During the last few decades the number of trapnets has gradually decreased, owing mainly to severe marketing problems during the spring season. On the other hand, especially in autumn, there are small but permanent markets for good-quality, "fatty" herring. Most of these markets are supplied with herring caught by gillnets, traditionally a labour-intensive fishing method the catch of which must be marketed immediately after capture. In the big, spacious bag of a poundnet, fish can survive in autumn for one to two weeks. This gives the fisherman essential extra time for marketing and organizing the transport of his catch. Consequently, poundnets would be well suited to the autumn fishery, but they have been used only in exceptional cases, owing mainly to the low catch rates achieved in autumn by the traditional trapnets.

The present work describes the first phase of a project which will study the fishing efficiency of a herring poundnet in autumn conditions, and clarify the possibilities of extending the poundnet season into the autumn.

Material and methods

Fishing trials were conducted in the autumns of 1989–1991 in a traditional poundnet fishing area in the central part of the Archipelago Sea (ICES Subdivision 29N). The poundnet used in the experiment is typical for the region (Fig. 1). It was, however, slightly modified by attaching a bottom net to the wings to prevent fish from escaping underneath.

In 1989 and 1990, the purpose of the trials was to collect basic information on the capture process and the proper construction and rigging of the gear. During the first autumn (1989), the leader net (18 mm bar length) had to be replaced with a 13 mm (bar length) leader to

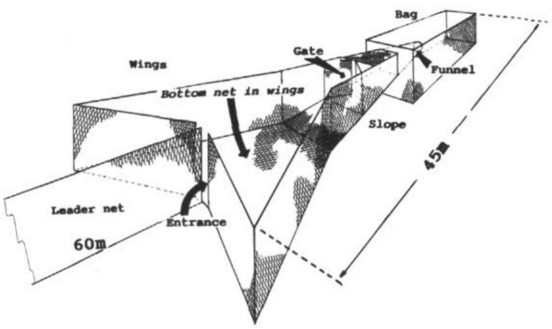

Figure 1. The poundnet used in the experiment is a typical model for the Archipelago Sea. Detailed design and rigging varies in different parts of the archipelago.

prevent herring from becoming meshed. However, small herring (<15 cm) were still found in the meshes of the leader, which strongly indicated that fish were trying to swim through the leader. It also appeared that environmental factors, such as heavy winds and stormy seas, had to be taken into consideration.

The bay chosen for the experiment in 1991 provided a location sheltered from winds and rough seas (Fig. 2). Fish densities in the bay and fish movements in relation to the poundnet were monitored by an echo sounder (Lowrance X-16) and experimental gillnets (15 m × 6 m, bar length 18 mm). Fixed transects for echo sounding (Fig. 2) were run from a small boat with a steady speed day and night between 26 September and 27 November. Recordings were also made with a stationary echo sounder placed in the vicinity of the leader net during the period 17 October to 27 November (in total 16 nights, 106 hours). Four experimental gillnets (altogether 65 nets) were set to nine different positions (Fig. 3) with short (30–45 min) and long (8–15 h) catching times. Fish caught in the two opposite sides of the gillnets were separated and the numbers were counted. The total catching time of the gillnets was 511 h (Table 1).

A stationary water current meter (Aanderaa model 4) was placed near the leader net 8 m below the surface from 26 September to 13 December (Fig. 3). The meter recorded the current direction and velocity at 60-min intervals. Water temperature, water surface level, and visibility in the bay were measured during the trial period.

Results

In autumn 1991, no big schools or aggregations of herring were found near the poundnet. A few small

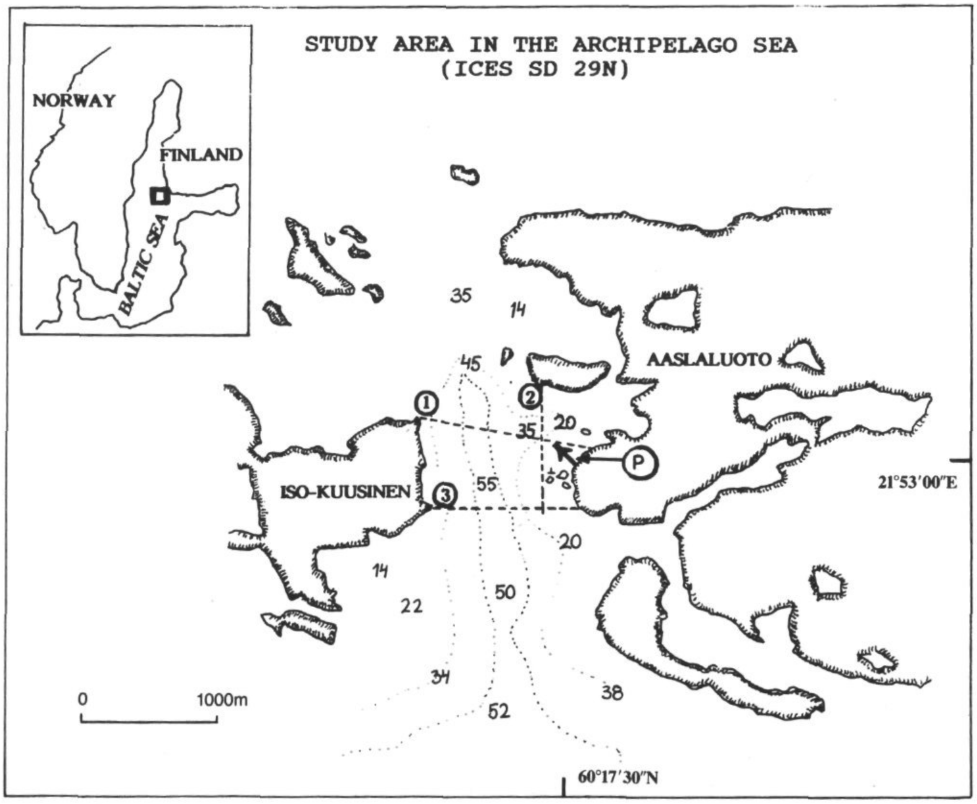

Figure 2. Location of the experimental poundnet (P) and trial area where the studies in 1989–1991 were conducted. Dashed lines denote fixed echo-sounding transects running east–west (1, 3) and north–south (2). Depths are shown in metres.

Table 1. The positions, number of nettings, duration of fishing and total catch of herring in the different positions of the experimental gillnets in autumn 1991. For the position of the nets see also Figure 3 (numbers in parentheses refer to numbers in Fig. 3).

Position	Nettings	Duration (h)	Catch (fish)
Wing (1)	20	159.8	2644
Mid (2)	14	136.7	5146
Shore (3)	4	43.9	404
South passage (4)	9	60.8	745
Along leader net (5)	4	5.8	161
Under leader net (6)	2	17.3	67
Under wing (7)	1	17.0	40
North/south (8)	4	7.0	161
East/west (9)	7	62.8	518
Total	65	511.1	9886

schools were recorded during dawn and dusk along the underwater slopes leading to the bay. However, during the dark period, considerable numbers of scattered herring swam into the bay. The highest gillnet catches, averaging 71 fish h^{-1} net^{-1} (var. 3 to 266 fish h^{-1} net^{-1}) (position 3) and 60 fish h^{-1} net^{-1} (var. 15 to 175 fish h^{-1} net^{-1}) (position 2), were found near the shore in a water depth of 5 to 15 m. High fish densities were recorded also in position 8, swimming north/south (Fig. 4). Peak gillnet catches of over 180 fish h^{-1} net^{-1} were made during the short period of 7–14 November. However, these high densities of fish around the poundnet did not increase the poundnet catches.

Most fish were caught in the layer 0–6 m below the surface. Gillnet positions 6 and 7 (with a fishing depth between 7 and 13 m) which had significantly lower catch rates indicated the same result. Echo sounder recordings showed that the highest fish densities were 3–4 m below the surface.

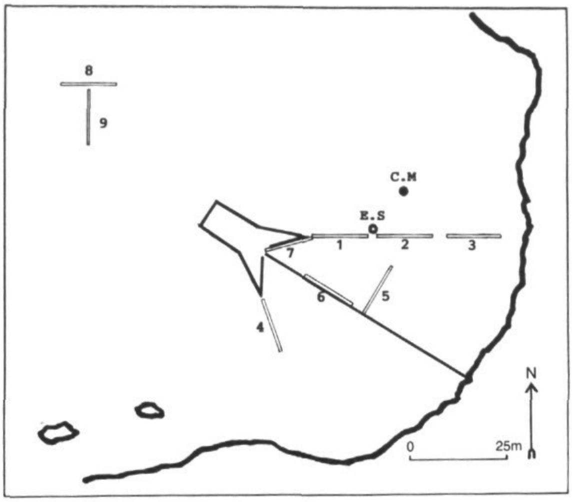

Figure 3. Positions of experimental gillnets around the poundnet (1–7) and in the bay (8, 9). A current meter (C.M) and stationary echo sounder (E.S) were also placed in the vicinity of the poundnet.

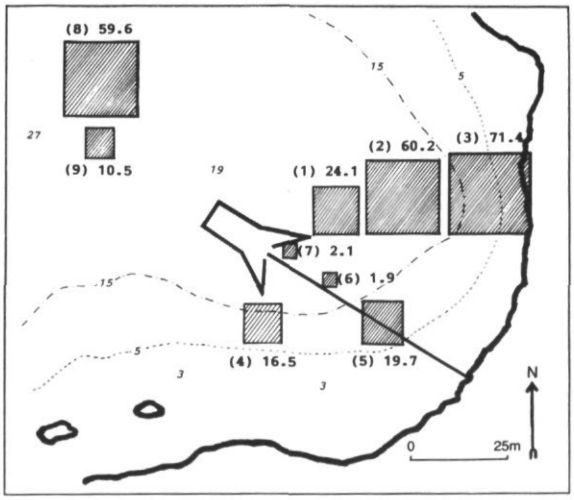

Figure 4. Average catch per unit effort (c.p.u.e.) of gillnets (fish h^{-1} net^{-1}) in different positions (numbers in parentheses) during the autumn of 1991. The highest herring density was found near the shore (positions 2, 3) in 5 to 15 m water depth and in the bay (position 8).

During the 1991 season the total herring catch of the experimental poundnet was 1.4 tonnes (3.7 tonnes in 1990, 1.4 tonnes in 1989). The poundnet catches displayed similarities, with a short peak in late October to early November, during which the water temperatures were 8 to 10°C (Table 2). Catches decreased at the beginning of December as the water temperature fell near 5°C. The average length of herring in the poundnet catches increased gradually from 15.5 cm to 16.5 cm during the fishing period 1991.

Current direction and velocity varied continuously. Both parameters could turn up with opposite values after 60 min. Two main current directions with a dominating southwesterly direction were distinguishable. The velocity varied from 1.5 to 13.0 cm s^{-1} (average of 4.1 cm s^{-1}) in the southwesterly direction and from 1.5 to 11.3 cm s^{-1} (average of 3.3 cm s^{-1}) in the north-

Table 2. Surface water temperature (°C) in the trial area during the autumns of 1989–1991.

	1989	1990	1991
21 Sep	15.2	14.4	13.1
1 Oct	14.7	13.6	11.4
11 Oct	13.5	11.9	11.2
21 Oct	11.5	10.5	9.7
1 Nov	10.3	9.4	9.2
11 Nov	9.4	8.4	8.4
21 Nov	9.1	7.3	6.2
1 Dec	7.5	6.3	5.1
11 Dec	5.7	4.8	4.3

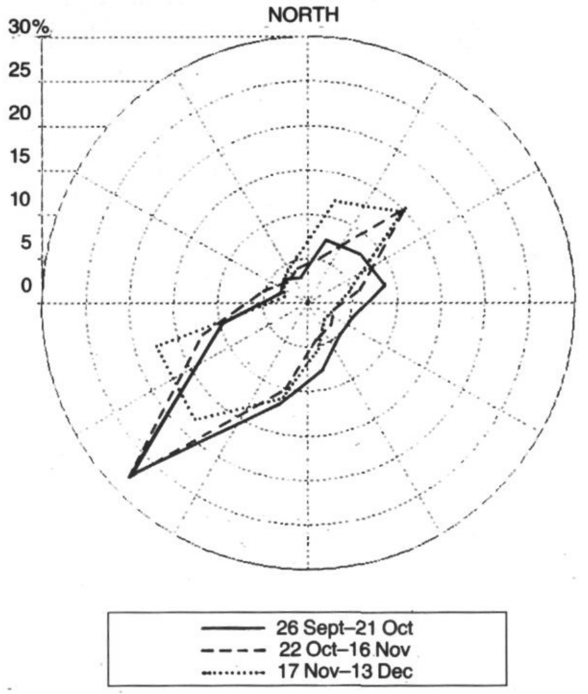

Figure 5. Frequency distribution of 12 classes of current directions divided into three time periods (3 polygons). The concentric circles stand for value axes (0%–30%) and the 12 sectors are the direction classes. E.g. during 26 Sept.–21 Oct., 27.6% of the current meter readings were between 210° and 239°.

easterly (Fig. 5). Gillnet catches showed higher densities of fish on the north side (current side) of the leader net (Fig. 4) and revealed that large amounts of herring were returning from the leader net to the direction from which they came (Fig. 6). This phenomenon was strongest near the current-side wing (Fig. 6, position 1).

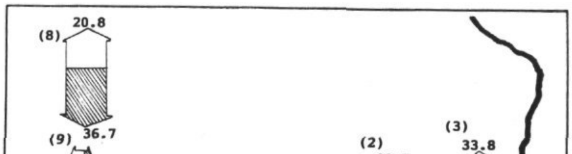

Figure 6. Average amount of herring (fish h^{-1} net^{-1}) swimming in different directions (numbers in parentheses refer to gillnet positions in Fig. 3).

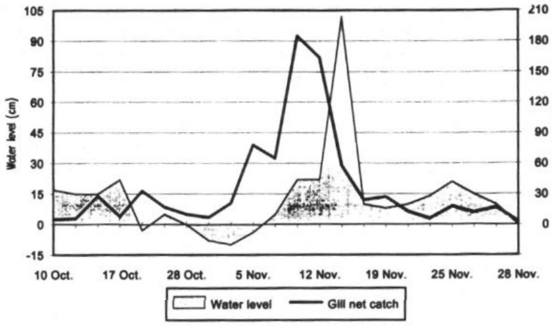

Figure 7. Water surface level and average diurnal gillnet catches (fish h^{-1} net^{-1}) in the bay in autumn 1991.

In the study area fluctuation in water level is normal during autumn and is caused by changes in atmospheric pressure and winds. The trial in 1991 included only one period with a relatively large change in water level. The observed changes were a minimum of −17 cm and a maximum of +102 cm. During this period (7–14 November) the average diurnal gillnet catch for the whole trial area showed the highest catch rates (Fig. 7). Visibility in the water varied from 3.2 to 6.5 m and was lowest in the bay after strong winds and heavy water movements.

Discussion

According to the results obtained, the number of herring in the bay increases at night-time. A similar kind of diurnal swimming pattern prevails during spawning time in the spring (Suuronen and Lehtonen, unpub.). This behaviour pattern creates the potential to conduct a poundnet fishery in shallow water with the same kind of traps as are used in the spring fishery. Preliminary trials with artificial light have shown that the behaviour of herring can be manipulated with underwater lamps (Beltestad and Misund, 1988; Tschernij and Lehtonen, 1990). The possibility of using underwater lamps to attract adult herring into the fishing ground of a poundnet should be studied.

The length of the autumn season seems to be restricted by water temperature. At the beginning of December, when the water temperature usually falls near 5°C, poundnet catches decrease. The same trend has been observed in the professional gillnet fishery in the trial area. Another problem, typical of the innermost parts of the Archipelago Sea, is the small size of the captured herring.

The main problem in the capture process of a poundnet in autumn seems to be connected to the behaviour of herring in relation to the leader net. In our experiments, the guiding function of the leader net was not satisfactory, even when the netting was made up of very small meshes. Even though a considerable number of herring were probably coming into contact with the leader net, only a few of them swam along it into the poundnet. Owing to the very dark nights in autumn, the herring may lose visual contact with the leader net. Blaxter and Hunter (1982) report a threshold light intensity for net avoidance. Recent results obtained during the spring season showed that by increasing the mesh size of the leader net in very turbid (dark) water, the guiding effect of the leader net may clearly be decreased (Suuronen, 1989). Järvik (1985) reported that bigger catches were obtained in the Estonian coastal trapnet fishery by using a leader net made of white instead of dark netting.

The higher fish densities on the current side of the poundnet indicate that herring are at least to some extent guided by water currents during the dark period. The relation between changes in water surface level and experimental gillnet catches indicates that water movements have an important effect on the swimming pattern of herring. It is common knowledge among coastal fishermen in Finland that changes in water level are followed by changes in herring catches. Blaxter and Hunter (1982) refer to occasional passive transport of North Sea herring caused by water currents. Inoue and Arimoto (1989) reported on scanning sonar observations made along the coast of Japan, where the route of many fish species (flying fish, salmon, spotted mackerel) was basically regarded as corresponding with the flow of water in the fishing grounds.

Because the recording intervals of the current meter were too long, the relationship between herring returning from the leader and the prevailing current direction remained unexplored. However, the clear dominance of the two main current directions in the vicinity of the leader net was indisputable and may explain the two main swimming directions. This assumption will be tested in autumn 1992 on the same fishing ground by rigging the leader net and the poundnet parallel (isobathically) to the main water current.

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The reliability and value of studies of fish behaviour in long-line gear research

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Løkkeborg, S., Bjordal, Å., and Fernö, A. 1993. The reliability and value of studies of fish behaviour in long-line gear research. – ICES mar. Sci. Symp., 196: 41–46.

The reliability and value of findings from studies of fish behaviour in relation to long-line gear are examined. Observations from behavioural studies in the laboratory and in the field and results from fishing trials are compared with regard to the behaviour of fish in relation to baited hooks and the efficiency of different hook and bait types. It is concluded that observations of fish behaviour are important, create ideas for improvements to gear, and provide explanations for results from fishing trials. Behavioural observations of the hooking process and of the role of visual stimuli (e.g., bait size) give reliable results, whereas quantitative studies and attraction of fish to chemical stimuli are regarded as less appropriate subjects for a behavioural approach. The advantages of conducting behavioural studies in the field rather than in the laboratory are also discussed.

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Introduction

It is commonly accepted that knowledge of fish behaviour is essential when developing new or improving existing fishing gears. However, conditions in an experimental situation, whether in the laboratory or in the field, may differ from actual fishing. The question is therefore how reliable results from observations of behaviour can be, for example when testing different gear parameters. The explanatory value of behavioural studies for results obtained in comparative fishing experiments also depends on how representative such observations are.

Long-line fishing gear can be investigated at different levels, ranging from laboratory and field studies of behaviour to experimental fishing and full-scale fishing trials. We try to illustrate the reliability of behavioural studies, using selected studies which involved more than one level of investigation. We also discuss the optimum timing of behavioural studies in a gear improvement programme and whether such studies should be carried out in the laboratory or in the field.

Levels of investigation

Many studies of fish behaviour with relevance to long-line gear have been made in the laboratory. These studies have dealt with various fields: the relative importance of different senses for the localization of prey (Brawn, 1969), the search behaviour of fish in relation to chemical stimuli (Kleerekoper *et al.*, 1975; Pawson, 1975), and the identification of feeding stimulants (Carr, 1982; Mackie, 1982). Reactions to different hook and bait types have also been studied in the laboratory (Lee *et al.*, 1989, 1990; Huse and Fernö, 1990; Johannessen *et al.*, 1993) .

Few studies have been made at the second level, i.e. behavioural observations of fish in their natural environment. Some observations have been made at the shoreline (Sutterlin, 1975; Johnstone and Hawkins, 1981), from small boats (Fernö *et al.*, 1986), and from oil platforms (Løkkeborg *et al.*, 1989). These studies have focused on the effectiveness of different chemical substances with regard to attraction (Sutterlin, 1975), and on diurnal rhythms of feeding activity and the reactions of fish to baited hooks (Fernö *et al.*, 1986; Løkkeborg *et al.*, 1989). Species differences in hooking behaviour and the efficiency of different hook and bait types have also been investigated (Johnstone and Hawkins, 1981; Fernö *et al.*, 1986; Løkkeborg *et al.*, 1989; Huse and Fernö, 1990).

The third level of study is experimental fishing that primarily has been carried out on commercial long liners, for example by comparing alternate hooks or clusters of hooks of different types. Such experiments have been conducted to test the importance of chemical stimuli (Løkkeborg and Johannessen, 1992), the effect of fishing time (Sivasubramaniam, 1961; Skud, 1978), bait loss (Shepard *et al.*, 1975; Skud, 1978) and swivel-mounted gangions (Bjordal, 1985), and the selectivity and efficiency of different hook and bait types (reviewed by Løkkeborg and Bjordal, 1992).

The fourth level and final test of a gear parameter is full-scale, long-term fishing trials, in which the modified gear is deployed in commercial long lining and tested for a whole fishing season (Bjordal, 1983).

The advantages and disadvantages of the different levels of study are summarized in Table 1. In the laboratory, the fish are easily controlled and observed, but adaptation to laboratory conditions and an abnormal motivational state can introduce severe artefacts. The limited volume of water makes investigations of searching behaviour difficult (Sutterlin *et al.*, 1982), and fish may rapidly accommodate as experience with the experimental situation can modify their behaviour (Fernö and Huse, 1983). Most of these problems are overcome in behavioural studies in the field, but as changes in fish density and activity rhythms may cause variations in response strength (Løkkeborg *et al.*, 1989), relative rather than absolute measures of effectiveness should be used (Sutterlin, 1975). Experimental fishing and full-scale fishing trials provide conclusive evidence of the effect of a gear modification, but they demand a great deal of effort and have limited explanatory value.

Fish behaviour in relation to baited hooks

The behaviour of cod towards a baited hook has been studied in the laboratory (Fernö and Huse, 1983) and in the field (Løkkeborg *et al.*, 1989). Both studies showed that in a typical sequence of behaviour, the fish first bites the bait, often after tasting, then swims away with the ingested baited hook, characterized as "jerk" or "rush" behaviour by Fernö and Huse (1983). The sequence is terminated when the baited hook is pulled or spat out of the mouth or when the hook engages in the fish; the latter event is most likely to occur after a "jerk" or "rush" response.

However, there are differences between the laboratory and the field with regard to the frequency of occurrence of the different behaviour patterns (Fig. 1). In the field, complete bite and high-intensity behaviour patterns such as jerk and rush were frequently observed, leading to a high probability of hooking (0.37, calculated as the ratio between the number of hookings and number of bites), whereas in the laboratory an incomplete bite was more frequent, giving a much lower probability of hooking (0.05). The intensity of the responses and the probability of hooking decreased in the laboratory after experience with the baited hook (Fernö and Huse, 1983). This modification of behaviour was not observed in the field because cod rarely made more than one response towards the baited hook (Løkkeborg *et al.*, 1989). Another difference is that hooking of fish often scared away fish in the laboratory (unpubl. observations), whereas hooked fish attracted other fish in the field (Fernö *et al.*, 1986; Løkkeborg *et al.*, 1989). This

Table 1. The major advantages and disadvantages of four different methods of behaviour study in relation to long-line gear.

Level	Advantages	Disadvantages
Behavioural studies in the laboratory	Control of fish availability and environmental conditions Ideal observation conditions Individual fish can be observed Low cost	Adaptation to laboratory conditions Conditioning to food Motivational state may differ from that of wild fish Conditioning to gear Difficult to establish chemical gradients
Behavioural studies in the field	Representative observations of wild fish	Absolute conditions differ Restricted observational area Time-consuming
Comparative fishing experiments	Strong indications of the effect of a gear modification	Give limited explanations of the results High effort and cost
Full-scale long-term fishing trials	Conclusive evidence of fishing effectiveness	Give limited explanations of the results Convincing evidence from previous levels required Dependent on cooperation with fishermen

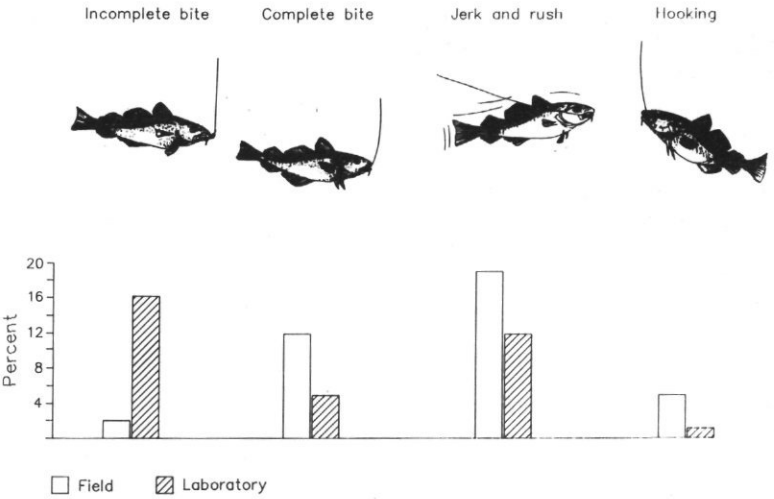

Figure 1. Comparison between responses of cod to a baited hook in the laboratory (from Fernö and Huse, 1983) and in the field (from Løkkeborg *et al.*, 1989). As the percentages of only four of the observed patterns of behaviour are shown, these do not add to 100%.

difference may be explained by a difference in the motivational state, as fish in the laboratory may be stressed.

Thus, the conclusion obtained in the laboratory, i.e. that "jerk" and "rush" behaviour leads to hooking, can be transferred to the natural environment, whereas quantitative results from laboratory studies, e.g. hooking probability, may be invalid.

Hook design

Huse (1979) conducted a comprehensive study which aimed to improve hook design. His study included observations of fish behaviour in the laboratory and in the field, as well as comparative fishing trials. Huse (1979) suggested that a hook with its point towards the line of pull would give a higher probability of hooking than the traditional J(Norway)-hook (Fig. 2). One hook design that fulfilled this requirement was the Wide Gap hook (Fig. 2). Behavioural studies in the laboratory indicated that the Wide Gap hook had a higher hooking probability for cod (0.36) than the J-hook (0.15). In behavioural studies in the field, similar results were obtained for haddock. These results were confirmed in subsequent comparative long-line fishing trials, where the Wide Gap hook gave significantly increased catch rates, both for cod (12%) and for haddock (34%), in comparison with the J-hook (see Huse, 1979; Huse and Fernö, 1990).

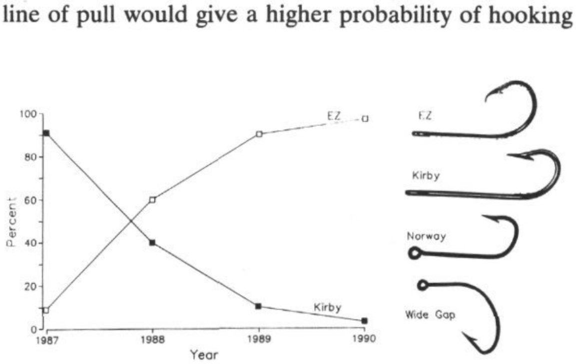

Figure 2. Traditional J-hooks (Norway and Kirby) and new, more efficient hook designs (Wide Gap and EZ-Baiter). The curves show the marked change in per cent of hooks sold, from J(Kirby)-hook (filled squares) to EZ-hook (open squares), in the Norwegian long-line fishery. (Based on sales statistics from O. Mustad & Son.)

Full-scale fishing trials with the Wide Gap hook during the spring fishery for cod off Finnmark (northern Norway) confirmed the superiority of this hook design. The Wide Gap hook gave higher catch rates than the J-hook, with an average increase in catch of 17% (Bjordal, 1983).

Later, the EZ (Easy Baiter Circle) hook was shown to give significantly increased catch rates compared with the J(Kirby)-hook (Skeide *et al.*, 1986; Bjordal, 1987). The EZ hook (Fig. 2) also fulfils the "point towards the line of pull" requirement with its bent point, and can be used with mechanized long-line systems. The Wide Gap and the EZ hooks are now widely used in the Norwegian long-line fishery, in the handbaiting and autoline fleets, respectively. Figure 2 demonstrates the increasing use of the EZ hook in the Norwegian long-line fishery.

Bait size

Comparative fishing experiments have shown that smaller baits gave significantly higher haddock catch rates than larger baits (Johannessen, 1983). These

Table 2. Frequency of categorized behavioural patterns of cod towards artificial (Art.) and natural (Nat.) baits observed in laboratory and field studies. For definitions of behavioural patterns, see Løkkeborg *et al.* (1989).

Trial	Bait	Approach	Taste	Bite	Chew/pull	Jerk/Rush	Bait out/ Hooking
Laboratory	Art.	1	29	28	29	53	28
	Nat.	3	30	21	15	29	21
	Ratio*	0.33	0.97	1.33	1.93	1.83	1.33
Field	Art.	12	60	15	7	34	15
	Nat.	14	39	13	4	20	13
	Ratio*	0.86	1.54	1.15	1.75	1.70	1.15

* Ratio of the frequency of behaviour patterns towards artificial and natural bait, respectively.

findings may be explained by behavioural observations. Laboratory studies of haddock showed that responses to a large bait were more often terminated without physical contact with the bait than were responses to a small bait (Johannessen *et al.*, 1993). Field studies showed that haddock usually bite at parts of the bait (Løkkeborg *et al.*, 1989), and this behaviour will probably cause a higher probability of haddock biting hooks baited with smaller baits. Thus, restrained response to large baits and higher hooking probability for hooks baited with small baits explain the higher catching efficiency of the latter.

In fishing experiments for cod, bait size did not affect catching efficiency (Johannessen, 1983). Field observations showed that cod usually sucked the whole bait into the mouth (Løkkeborg *et al.*, 1989). Bait size therefore does not influence the hooking probability of cod to the same degree as for haddock. However, fishing experiments showed that bait size affected the size selectivity of cod catches; smaller baits caught more small fish than larger baits (Johannessen, 1983; Løkkeborg, 1990).

Artificial bait

Behavioural studies in laboratory and field

Behavioural responses of cod to a shrimp-flavoured artificial bait and natural mackerel bait were compared, both in the laboratory and in the field (unpubl. data, see Table 2). The ratios of the frequency of occurrence of the different behavioural patterns towards artificial and natural baits were similar in the laboratory and in the field. This agreement indicates that similar conclusions can be drawn from laboratory and field studies about the relative effectiveness of different bait types, as regards palatability, texture, and appearance (size and shape). In the laboratory study, approaching and tasting both bait types happened less frequently than in the field. Baits were put in bags and not baited on hooks in the laboratory, and stimulation of the taste receptors when biting the bait may have caused positive reinforcement of the behaviour.

Behavioural studies and fishing trials

Sutterlin *et al.* (1983) compared different types of artificial bait with natural bait, and found that some of the artificial baits were as effective as natural bait when tested in the laboratory. When tested in fishing trials, however, all these baits compared poorly with natural bait. This may be due to the artificial baits being ineffective in attracting fish to the baited long line even though the artificial bait stayed well on the hook. The value of laboratory screening of the attractiveness of artificial baits is therefore limited.

The behaviour of haddock and cod towards an alternative long-line bait based on a nylon bag enclosure for mechanical reinforcement has been studied in the field (unpubl. data). For both haddock and cod, the hooking probability was lower for bag-enclosed bait (40 and 47% of that of natural bait, respectively), suggesting an inhibition of bait intake and swallowing response, perhaps owing to the texture of the nylon bag. Corresponding results were obtained in fishing trials for haddock and cod with bait in the same bag enclosure, giving 21 and 63% of the catch rate of natural bait, respectively (Løkkeborg, 1991). This correspondence indicates that behavioural studies may be useful when testing bait texture.

Discussion

The results presented here demonstrate that observations of fish behaviour are essential for understanding the catching process of long-line gear. The value and significance of behavioural studies for gear improvements are therefore beyond doubt. Behavioural studies are particularly important for generating ideas for improved gear design, and should be made at the initiation of a gear improvement programme to provide a framework into which subsequent findings can be fitted. Observations of behaviour can have value during later stages of the research to explain results and test hypotheses arising in the course of fishing trials.

The behavioural repertoire of a species tends to be rather limited (Atema, 1980; Løkkeborg, 1989), and the general behavioural patterns and physical forces generated are therefore regarded as similar in behavioural studies and in an actual fishing situation. The similarities in the behaviour of fish being hooked when observed in the laboratory and in the field, and the results with the Wide Gap hook in fishing trials support this assumption.

Visibility in water is limited and visual stimuli can only be observed by fish in the near field (Guthrie, 1986). This should be an advantage for behavioural studies that investigate the role of visual stimuli in the catching process. The similarity between the results of reducing bait size in the laboratory and in fishing experiments confirms that observations of the effectiveness of visual stimuli give relevant results (Johannessen, 1983). Likewise, sensing texture requires physical contact with the bait, and similar conclusions were drawn from behavioural studies and fishing experiments with a bait encased in a nylon bag.

Nevertheless, several difficulties arise when studying the reaction of fish to chemical stimuli. The phases of attraction and location are not easily studied in the laboratory because of short distances and limited volumes of water. In the field, limited visibility and variations in fish density and activity rhythms will complicate such studies. Behavioural studies on taste preferences in the laboratory may be influenced by the food given in captivity and by positive reinforcement (Solemdal and Tilseth, 1974). In addition, when the effectiveness of different bait types is being tested, potential differences in the release rate of attractants and the rate of bait loss are difficult to identify in both laboratory and field studies. Chemical attraction is thus regarded as a less appropriate subject for a behavioural approach. Such studies may, however, show relative differences in stimulatory capacities between different feeding stimulants and bait types, and fish with ultrasonic tags could be useful in observing chemically stimulated attraction responses in the field.

The advantages and disadvantages of behavioural studies in the laboratory and in the field have been summarized in Table 1. The general conclusion is that, apart from an introductory phase, behavioural studies in relation to baited hooks should be made at sea. Observations in the laboratory can provide valuable information, e.g. from detailed hydrodynamic analyses of the hooking process (Lee *et al.*, 1989, 1990), but conditioning to the experimental situation and adaptation to laboratory conditions represent serious problems. These difficulties are overcome in the field. The crucial factor is to find a location with high concentrations of fish and good experimental conditions, such as an oil platform (Løkkeborg *et al.*, 1989).

Several examples in this paper have shown that the results obtained by behavioural studies are confirmed in subsequent fishing trials. However, it should be emphasized that the results of behavioural studies, and to a certain degree results obtained during experimental fishing, should be regarded as qualitative. There are several reasons for this. Values of hooking probability can be derived from behavioural studies, but not true catch rates, because multiple attacks towards the hook and escapes are not counted. Furthermore, behavioural studies are often focused on the target species only, and exclude such factors as gear satiation and competition for the baited hooks. Likewise, the results from experimental fishing might be quantitatively biased because the trials are conducted within limited time periods, and might therefore not be representative owing to seasonal changes in fish availability and species composition. The experimental design has also been shown to affect the results, as small units of comparison (e.g. every second hook) may exaggerate the differences in catch rate between hook types (Bjordal, 1982). Reliable quantitative differences in catch rates when testing different gear parameters are therefore only achieved through long-term trials in commercial fishing.

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Behaviour of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in relation to various sizes of long-line bait

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Johannessen, T., Fernö, A., and Løkkeborg, S. 1993. Behaviour of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) in relation to various sizes of long-line bait. – ICES mar. Sci. Symp., 196: 47–50.

The behaviour of cod (*Gadus morhua* L.) and haddock (*Melanogrammus aeglefinus* L.) in relation to various bait sizes was studied by simulating semipelagic long-lining in the laboratory. The fish were exposed to a hook baited alternately with mackerel baits of 10 g and 30 g. During the experimental period the behaviour of the fish gradually changed through learning. The behaviour during the first part of the experiment was therefore considered to be most relevant to field conditions. For both species the frequency of biting was significantly higher on small than on big baits. Haddock frequently bit at part of the big bait, leaving the hook outside the mouth, and would then jerk or rush to tear the bait apart, whereas hooks with small baits were usually completely ingested. In cod, on the other hand, there was little difference in behaviour towards the two bait sizes after biting. Owing to higher frequency of biting, one should expect small baits to give higher catch rates on semipelagic long-line than big baits for both cod and haddock. Furthermore, the complete ingestion of small baits should favour an increased catching efficiency for haddock. These observatons are in accordance with the results from fishing experiments in the field.

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Introduction

Fishing experiments at sea with semipelagic long lines have shown that bait size has a significant influence on both catching efficiency and size selectivity for cod and haddock (Johannessen, 1983). Different bait sizes caught approximately the same number of cod >60 cm total length, whereas small baits were more efficient for smaller cod. For haddock, bait size only slightly influenced catch size selectivity. However, baits of 10 g caught more than twice as many haddock as 30 g baits. The results of the fishing trials provided no evidence about the cause of the observed differences. It was assumed that the variation in catch reflected the prey size preferences of cod and haddock, or that larger baits may result in less efficient hook engagement and capture.

This paper describes laboratory studies of the behaviour of cod and haddock towards different bait sizes. The main objective was to explain the observed catch difference between small and big baits in semipelagic long-lining. The paper also gives a detailed description of the behaviour of the fish in relation to a baited hook, and the results may be relevant to general prey size preferences of cod and haddock.

Material and methods

Experimental design

The behavioural studies were carried out indoors in a concrete tank which formed a 2 m wide circular channel with a circumference of 31 m along the inner wall and had a water depth of 2.3 m. The experiment with cod took place in October/November. The cod, 26 individuals with an average total length of 55.5 cm (range 46–72 cm), were caught in traps and gillnets on the west coast of Norway and kept for 21 days in the tank for adaptation. Prior to the experiment more than half the cod were eating (except for test-feeding to examine how the adaptation improved, the fish were not fed). One cod died during the experimental period of 13 days.

The experiment with haddock took place in May/June. The fish were caught by beach seine three days prior to delivery. Thirty haddock with an average total length of 55.1 cm (46–61 cm) were transferred to the observation tank. The fish adapted quickly, and after a fortnight most of the haddock were eating (test-feeding only). Five haddock died during the experimental period of 24 days.

A monofilament, polyamide long line (4 m) was placed in front of an observation window. One barbless hook (Mustad Norway no. 5, qual. 7296) with a 40 cm gangion was attached to the test line. The line was rigged to simulate the performance of semipelagic long lines with respect to flexibility. Also factors such as bait type, bait dimension and baiting technique were in accordance with the fishing trials at sea. The light in the laboratory was kept on both day and night to simulate the conditions in the Barents Sea during the polar summer. The water temperature in the tank was 8°C (±0.3).

The experiments were carried out by comparing the behaviour of the fish towards mackerel baits of 10 and 30 g. The length and width of 10 g baits were 3.8 and 2.0 cm respectively, and of 30 g baits 8.3 and 2.3 cm. The thickness of the bait was adjusted to give the appropriate weights, and hence varied according to which part of the mackerel fillet the bait had been cut from. The two bait sizes were tested in alternating trials. Each trial lasted for 10 min or until a fish was hooked. There was a 5 min break between trials. The starting bait size was altered from day to day. The number of experiments per day varied between two and four, depending on the response of the fish. Seventeen trials with each bait size were conducted in the experiment with cod, and 20 trials with each bait size in the experiment with haddock. Hooked fish were carefully removed from the hook and released into the tank again.

Behavioural patterns

The behaviour of the fish was videotaped for later analysis. The observed behaviour was sorted into the following categories:

Approach (A) – swimming towards the baited hook, but turning before touching the bait.
Taste (T) – touching the bait with the lips or the barbel (if followed by another behaviour pattern, the taste had to last for at least 2 s to be recorded).
Incomplete bite (iB) – sucking the bait into the mouth without closing the mouth.
Bite the bait (bB) – biting the bait while part of the bait remained outside the mouth.
Complete bite (cB) – sucking the whole bait into the mouth and closing the mouth.
Bite (B) – either iB, bB or cB.
Chew (C) – chewing on the bait.
Jerk (J) – a rapid movement of the head with the bait in the mouth.
Slow jerk (sJ) – a low-intensity jerk.
Rush (R) – swimming rapidly with the bait in the mouth.
Pull (P) – swimming slowly with the bait in the mouth (a slow rush).
Bait out of mouth (O) – spitting out the bait or the bait being pulled out of the mouth.
Hooking (H) – retaining the hook in the mouth for at least 30 s while the fish fought violently.

A behaviour sequence was defined as a series of these categorized behaviour patterns, starting with the fish approaching the bait and terminating when the fish became hooked or turned away from the bait. The behaviour of the fish was evaluated on the basis of three phases: (1) attacking phase (consisting of A, T, iB, bB, cB), (2) handling phase (C, J, sJ, R, P), and (3) terminating phase (O, H).

Owing to possible effects of learning, the experiments were split into four periods, with approximately the same number of behaviour sequences in each period. Hence, the four periods were equal neither in time nor in number of trials. If there was no significant change in behaviour during the four periods ($p > 0.05$, chi-square heterogeneity test), the four periods were pooled to evaluate the behaviour of the fish. On the other hand, if behaviour changed significantly, only data from period 1 were included since the very first attacks probably are most relevant to actual fishing.

Results

Cod

There was a significant change in behaviour of cod during the four experimental periods in the attacking phase ($p = 0.001$, chi-square heterogeneity test). In period 1 the frequency of complete bite (cB) on 10 g baits was approximately 2.5 times as high as that on 30 g baits (Table 1). Cod more frequently approached and tasted the 30 g baits. In subsequent periods the frequency of complete bite dropped significantly and became the same on both bait sizes.

In the handling phase there was no significant change in the behaviour of cod during the experimental period ($p = 0.303$, chi-square heterogeneity test), and behaviour towards 10 and 30 g baits was similar ($p = 0.413$, chi-square contingency analysis). A total of 7 and 5 cod were caught on 10 g and 30 g baits respectively. These numbers are too low to evaluate the hooking probability on the two bait sizes. All hooking took place after a jerk or a rush, both being behaviour patterns of high-intensity movement.

Table 1. For cod, number of observations and the relative frequency (%) of the various behaviour patterns* in relation to 10 and 30 g baits in the attacking phase (period 1 only) and in the handling phase (all four periods), and the observed number of behaviour patterns in the terminating phase.

Bait size	Attacking phase						Handling phase						Term. ph.	
	No.	A	T	cB	iB	bB	No.	sJ	J	R	P	C	O	H
10 g	57	25	16	49	10	0	147	39	46	9	2	5	103	7
30 g	59	48	27	19	5	2	140	31	53	11	4	1	75	5

* Behaviour patterns: A, approach; bB, bite the bait; C, chew; cB, complete bite; H, hooking; iB, incomplete bite; J, jerk; O, bait out of mouth; P, pull; R, rush; sJ, slow jerk; T, taste. See text for definitions.

Haddock

The behaviour of haddock in the attacking phase did not change significantly during the experimental period (p = 0.950, chi-square heterogeneity test, Table 2). However, haddock attacked the two bait sizes differently (p = 0.001, chi-square contingency analysis). The frequency of complete bites of 10 g baits was more than twice as high as that of 30 g baits, whereas haddock bit the bait (bB) more often when attacking 30 g baits. Haddock also more frequently tasted big baits. After tasting, the fish swam away on 90% of occasions. Incomplete bite was only of minor importance and the number of approaches was about the same towards both bait sizes.

The handling behaviour of the haddock did not change significantly during the experimental period (p = 0.723, chi-square heterogeneity test). However, haddock handled small and big baits differently (p = 0.001, chi-square contingency analysis), with slow jerk being more frequent for 10 g baits and jerk more frequent for 30 g baits. The frequency of rush was similar for both bait sizes, whereas pull and chew were of minor importance. The catch rates were significantly higher on small baits than on big baits when estimated on the basis of the number of bites (B, p = 0.049, chi-square analysis).

Because of the higher catch rates on 10 g baits, the total experimental time with this bait size was considerably lower than that with 30 g baits. In the first half of the experimental period (periods 1 and 2), the attack rate towards 10 g baits was significantly higher than that towards 30 g baits, with 3.11 and 1.93 attacks/min respectively (p = 0.005, chi-square analysis, the total numbers of attacks, T and B, towards 10 and 30 g baits were 64 and 72 respectively). In the second half the attack rate towards 10 g baits dropped to 0.97 attacks/min whereas it did not change towards 30 g baits (1.97 attacks/min, the total numbers of attacks were 54 and 88 respectively).

Discussion

During fishing experiments with hooks and lines, several authors have reported a decreased catchability of various species (Beukema, 1970a, 1970b; Hackney and Linkous, 1978; O'Grady and Huges, 1980). This is believed to be due to the development of hook avoidance. Fernö and Huse (1983) observed the behaviour of cod towards a baited hook and found that the intensity of the response was highest initially, with a modification of behaviour after experience with the baited hook. This is in accordance with the present findings. Consequently, the behaviour of cod when attacking the baited hook as observed in period 1 is probably the most relevant to behaviour in the field.

The behaviour of fish towards a single baited hook may differ from that in commercial long-lining, where many hooks are used. Fish caught on a semipelagic long line located above the seabed can swim some distance, and neighbouring hooks will therefore be moving rather than hanging still. Furthermore, cod making rapid and intensive movements seem to stimulate the feeding behaviour of other cod (Brawn, 1969), and fish fighting vigorously after hooking have been observed to stimulate other fish to attack neighbouring hooks (Fernö *et*

Table 2. For haddock, number of observations and the relative frequency (%) of the various behaviour patterns in relation to 10 and 30 g baits in the attacking phase and in the handling phase, and the observed number of behaviour patterns in the terminating phase. Results are from all four periods. Behaviour patterns are coded as in Table 1.

Bait size	Attacking phase						Handling phase						Term. ph.	
	No.	A	T	cB	iB	bB	No.	sJ	J	R	P	C	O	H
10 g	157	25	22	34	8	11	132	19	28	42	5	6	69	16
30 g	203	21	40	15	1	22	122	7	48	39	5	1	71	6

al., 1986; Løkkeborg *et al.*, 1989). Thus, fish attacking a single hook in the laboratory will have more time to judge the "quality of the prey organism". Therefore, the most likely effect of laboratory conditions is that behavioural differences towards the two bait sizes would be overestimated.

However, there is good agreement between the present study and fishing experiments with different bait sizes at sea (Johannessen, 1983). In the fishing experiments at sea, small baits gave higher catches of small cod (<60 cm), whereas the catches of larger cod were not affected by the bait size. The present study indicates that this effect probably was caused by small cod ingesting (cB) small baits more frequently than big baits.

For haddock, bait size has been shown to influence catch size selectivity only slightly, but, baits of 10 g caught more than twice as many haddock as 30 g baits (Johannessen, 1983). This may be explained by haddock attacking small baits more often than big baits, and also by more frequently ingesting (cB) small baits. When attacking 30 g baits, haddock often bit the bait (bB) and then usually jerked or rushed to tear the bait apart. This finding is in accordance with the fishing experiments at sea, where observations of the state of the bait at the end of fishing indicated that haddock nibbled on big baits but not on small baits (Johannessen, 1983). Løkkeborg *et al.* (1989), when observing behaviour towards a baited hook in the field, also reported that haddock more frequently bit the bait (bB) than did cod.

The present study indicates that haddock may attack food particles that are too big for its small mouth, and then try to tear it apart. Cod, on the other hand, only seem to attack food particles of appropriate size. This difference in behaviour of cod and haddock may explain why bait size influenced selectivity for cod but not for haddock.

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Behavioural differences of Atlantic salmon (*Salmo salar*) and whitefish (*Coregonus lavaretus*) as the basis for improving the species selectivity of whitefish trapnets

Anna-Liisa Toivonen and Richard Hudd

Toivonen, A.-L., and Hudd, R. 1993. Behavioural differences of Atlantic salmon (*Salmo salar*) and whitefish (*Coregonus lavaretus*) as the basis for improving the species selectivity of whitefish trapnets. – ICES mar. Sci. Symp., 196: 51–58.

Studies were undertaken in the Gulf of Bothnia, Finnish coast, to reduce the selectivity of whitefish trapnets for Atlantic salmon (*Salmo salar* L.). Trapnets for whitefish (*Coregonus lavaretus* s. str. L.) cannot be used during the spring spawning migration of Atlantic salmon because of the high by-catch of salmon. Several modifications to the traditional trapnet were tested. The nets were modified to catch whitefish and reject Atlantic salmon on the basis of differences in behaviour of the two species. One particular modification proved highly selective: a prohibiting net constructed of large-diameter twine was hung in front of the wings of the trapnet. Migrating salmon swim parallel to the surface and avoid the trapnet as they sense the prohibiting net. At this time of the year the whitefish approach the trapnet as they are eating benthic gastropods. The selectivity of the traps for whitefish is not reduced by the presence of a prohibiting net. Use of the prohibiting net reduced the by-catch of salmon by 62% (by weight) but did not affect the catch of whitefish.

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Introduction

Planting has increased the catches of Atlantic salmon (*Salmo salar* L.) in the Baltic Sea. Protection of the natural salmon is vital to the stock and its genetic variation. On the Finnish coast, the only two rivers left where the natural salmon reproduce lie at the northernmost end of the Gulf of Bothnia, Baltic Sea (Fig. 1). During the spawning migration of natural salmon in the spring and early summer of 1986–1991, all stationary gears were prohibited in the state-owned waters along the Finnish side of the Gulf. The regulation applied to all stationary gears because of their high by-catch of Atlantic salmon. Whitefish (*Coregonus lavaretus* s. str. L.) fishing was also badly suppressed by the restriction. A three-year project was started in 1989 to modify the whitefish trapnet and reduce its selectivity for Atlantic salmon.

The swimming habits of salmon during the spawning migration have been studied by Westerberg (1982b). The salmon tend to move along isothermal surfaces, preferably where the temperature is between 13 and 14°C. In the spring this layer is near to the surface of the sea. Occasionally the salmon dive briefly through all the thermal layers nearly to the bottom. Their maximum migrational swimming speed is two–three body lengths per second; the speed drops as they approach the river mouth. Salmon can sense trapnets and avoid them; they usually get caught by one trapnet when avoiding another (Westerberg, 1982a).

In the spring and early summer after the ice cover melts, whitefish eat gastropods on the hard shallow bottoms (Hudd and Svanbäck, 1987, Böhling *et al.*, 1991). Whitefish are trapped by trapnets from grounds near the seabed. It is typical of the whitefish trapnet that the leader arm and the wings extend from the surface of the water to the seabed (Toivonen *et al.*, 1992), whereas salmon trapnets are buoyant all over. Later in the summer, in June and in August, the migratory whitefish start their spawning migration, and swim near the surface as well as near the bottom. Thus, their behaviour changes later in the season. According to fishermen's

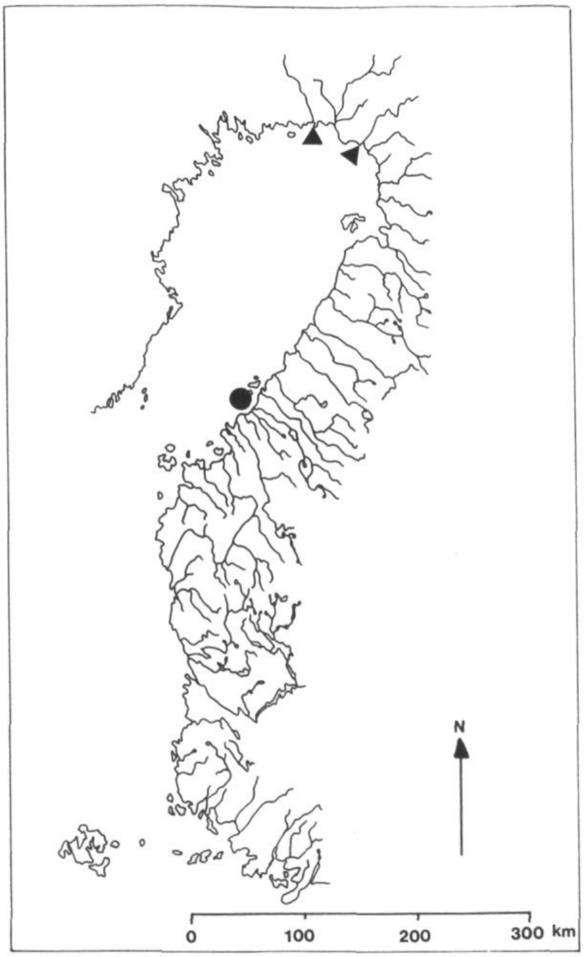

Figure 1. Gulf of Bothnia, Baltic Sea. The location of the experimental sites is marked with a circle and the rivers towards which the salmon were migrating on the Finnish coast are marked with triangles.

observations, whitefish behave calmly and swim slowly near and inside the gear. Salmon react vigorously when caught and may swim against the trapnet panels.

As the average weight of the migrating salmon caught in the spring is about 7 kg and the whitefish usually weigh less than 1 kg, the selection problem cannot be solved simply by altering mesh size. Differences in behaviour of the two species near and in the fishing gear provide the basis for developing more selective trapnets.

Materials and methods

Whitefish trapnets were modified and fishing experiments took place in the coastal waters of the southern part of the Gulf of Bothnia (Fig. 1). Professional fishermen fished in their traditional fishing sites. The depth of the fishing places was less than 20 m. Each type of experiment was conducted in different and locally restricted sites.

In the first experiment, six fishermen fished with two trapnets each for over two weeks. The trapnets were matched as pairs but one in each pair was equipped with thin black ropes from the end of the last funnel to the end of the last fish bag (Fig. 2), because according to fishermen, such ropes frighten salmon, reducing the catch.

The second experiment was based on the information that salmon become agitated when trapped. At first two trapnets were reconstructed so that the panels in the first two compartments were replaced by very-large-meshed polyethylene netting (Fig. 3). Comparison material was collected with a third, control trapnet with traditional 60 mm polyamide panels. The general idea was that the salmon would be alarmed and might escape through the large meshes, whereas the whitefish, being more calm, would remain inside the trap. A salmon net was set around the trapnet to catch any escaping salmon. The following year the experiment was repeated with a trapnet that had extra large meshes in the corners (Fig. 4) where salmon usually gill. The experiment lasted for six weeks in 1990 and for five weeks in 1991.

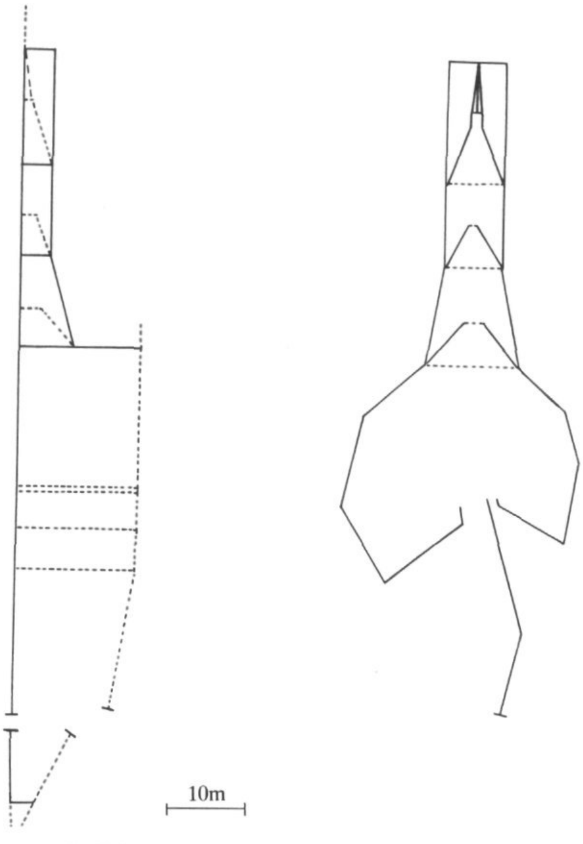

Figure 2. Side and aerial views of a trapnet set for whitefish. The ropes (see text) are set in the last compartment.

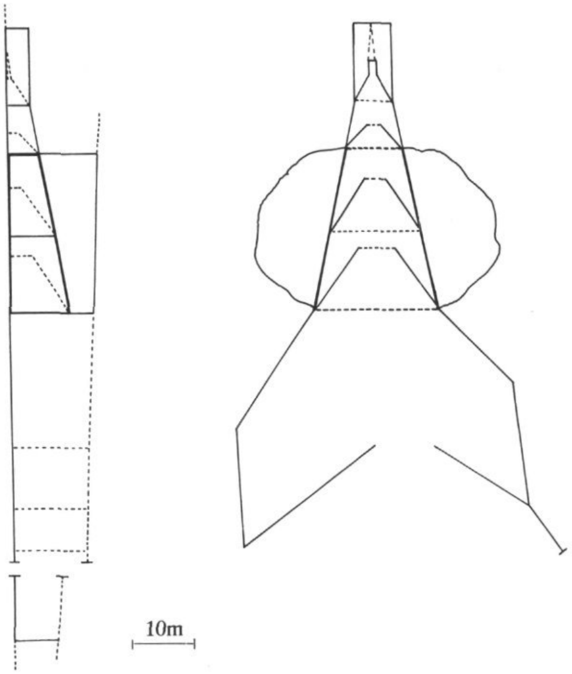

Figure 3. Side and aerial views of a trapnet set for whitefish. The first two compartments (heavy outline) are made of large-meshed polyethylene (PE) netting and surrounded by a gillnet to catch the escaping salmon.

The third modification was based on the assumption that salmon swim near and parallel to the surface and that whitefish swim near the bottom. A coarse prohibiting net was hung in front of the wings of the trapnet (Fig. 5). We expected that the migrating salmon would swim parallel to the surface and avoid the trapnet as they sensed the prohibiting net. The whitefish would approach the trapnet while eating benthic gastropods, ignore the prohibiting net hanging near the surface, and become trapped. Six pairs of trapnets were in use. Each pair consisted of one trap with, and one trap without, a 3-m-deep prohibiting net. The test was repeated later in the summer, in August, to see whether the assumed behaviour of the whitefish had changed towards its migration season. The experiment lasted for four weeks in spring and another three weeks in late summer.

Results

The total catch of salmon was reduced by 23% and that of whitefish by 15% when the last compartment of the trap contained ropes as shown in Figure 2 (Table 1). Mean daily catch varied among fishermen (Fig. 6). The catch of salmon was significantly lower in the modified trapnet in two cases of the six. The catch of whitefish was significantly lower in one case of the six.

Trapnets containing sections of large-meshed polyethylene caught significantly less whitefish than the conventional trapnet made of 60 mm polyamide (Table 2). In 1991 the catch of salmon was significantly lower in the experimental traps than in the control trap. The model with 80 mm polyethylene panels and 250 mm corners caught particularly few whitefish and salmon. On the other hand, according to catch statistics of the Finnish Game and Fisheries Research Institute, the catch of whitefish in general was smaller than previous years in both 1990 and 1991 in this area. The differences between catches of either salmon or whitefish if the mesh size was 150 mm or 200 mm were negligible. No salmon were caught in the salmon net that was set around the front parts of the trapnet.

The third modification, with a prohibiting net in front of the wings of the trapnet, proved to be very efficient in restricting the by-catch of salmon (Table 3a). In spring the total catch of salmon was reduced by the prohibiting net by about 60% relative to the control net, while the catch of whitefish remained practically unaffected. Later, in August, the catch of whitefish was somewhat

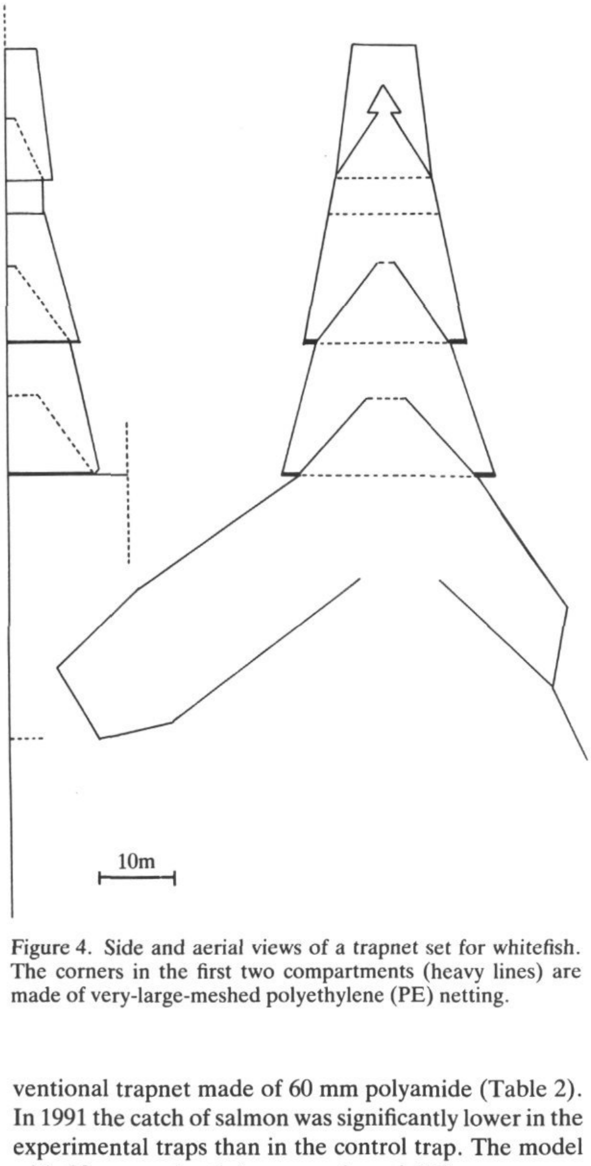

Figure 4. Side and aerial views of a trapnet set for whitefish. The corners in the first two compartments (heavy lines) are made of very-large-meshed polyethylene (PE) netting.

Table 1. Total catch of Atlantic salmon and whitefish from six trapnets with ropes in the last compartment and six control trapnets lacking such ropes. Standardized sum signifies that each type of trap has been standardized to have fished for 86 trap days between 26 May and 15 June, 1989. Values differing significantly are denoted by * ($p < 0.05$ in pairwise *t*-tests of standardized daily catches).

	Salmon		Whitefish	
	Ropes	Control	Ropes	Control
1989				
Sum (kg)	869	1 197	324	404
Standardized sum (kg)	923	1 197	344	404
	*	*		
Calendar days	19	19	19	19
Mean/trap day (kg)	10.7	13.9	4.0	4.7
S.e.	1.8	1.9	0.5	0.7
Trap days	81	86	81	86

decreased (17%) by the prohibiting net (Table 3b), but this difference was not statistically significant. The daily catches of salmon and whitefish in spring are presented in Figure 7. The graphs show that peak catches of salmon were much reduced by the prohibiting net. Every fisherman caught significantly less salmon in the trapnet equipped with the prohibiting net. The catch of whitefish in the modified trap was significantly greater than in the control trap of one fisherman of the six.

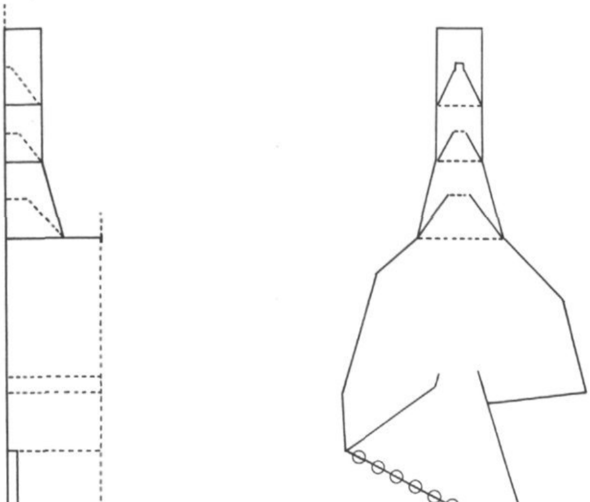

Figure 5. Side and aerial views of a trapnet set for whitefish. A prohibiting net is set in front of the wings (circles represent floats).

Discussion

Ropes from the end of the last funnel to the end of the trap decreased the by-catch of salmon, but the catch of whitefish was also affected. Therefore the ropes cannot be considered to have the desired effect on the by-catch. Additionally, it would be difficult for the authorities to control the existence of such ropes.

Traps with large-meshed polyethylene panels caught salmon reasonably well but not whitefish. The behaviour of the fish must have differed from what was anticipated. It seems that the whitefish swam through the big meshes in the front part of the gear. The use of polyethylene netting instead of polyamide proved, however, to have other advantages (Toivonen and Blomqvist, 1992), such as remaining clean for longer periods.

The results of tests with the prohibiting net were convincing. The by-catch of salmon was consistently lower in trapnets with a prohibiting net than in control trapnets during spring. The effect of the prohibiting net on the catch of whitefish supports the behavioural model, both in spring and in summer. In autumn, whitefish have always been widely fished with surface nets. This practice is based upon the same model of behaviour. The by-catch of salmon was reduced by the prohibiting net. The addition of such a net is feasible and relatively cheap, and the net can easily be removed if desired. Perhaps merely a rope with white floats would affect the by-catch. A rope with floats would be even easier for the authorities to verify, from the air for example. The fact that data were collected from a restricted area might limit use of the results; more experiments in other regions are needed to generalize the method.

Instead of closing trapnet fishing during the beginning of the Atlantic salmon spawning migration, prohibiting nets could be used. This strategy would enable trapnet fishing for whitefish. As a consequence of decreasing the by-catch of salmon in whitefish trapnets, half the salmon that the traps would otherwise catch would be able to continue their spawning migration. The distribution of the total catch of salmon along the coast would shift

Table 2. Total catch of Atlantic salmon and whitefish from two modified trapnets with large-meshed polyethylene panels in the first two compartments and from one control trapnet. Each type of trap was fished for 45 trap days between 28 May and 11 July 1990 and 33 trap days between 10 June and 15 July 1991. Values differing significantly are denoted by * ($p < 0.05$) and ** ($p < 0.01$) as determined by pairwise *t*-tests of daily catches.

	Salmon			Whitefish		
	200 mm	150 mm	Control (60 mm)	200 mm	150 mm	Control (60 mm)
1990						
Sum (kg)	368	349	542	47	47	117
				**		**
					**	**
Mean (kg)	8.2	7.8	12.0	1.0	1.0	2.6
S.e.	1.6	1.3	3.3	0.2	0.2	0.6
Trap days	45	45	45	45	45	45

	Salmon			Whitefish		
	200 mm	80 and 250 mm[a]	Control (60 mm)	200 mm	80 and 250 mm[a]	Control (60 mm)
1991						
Sum (kg)	334	276	559	90	54	401
	*		*	**		**
		*	*		**	**
				*	*	
Mean (kg)	10.1	8.4	16.9	2.7	1.6	12.2
S.e.	1.9	2.0	3.2	0.6	0.5	2.3
Trap days	33	33	33	33	33	33

[a] i.e. 80 mm panels and 250 mm corners (see text).

Table 3a. Total catch of Atlantic salmon and whitefish from six modified trapnets with a 3-m-deep prohibiting net in front of the wings and from six control trapnets. Each type of trap was fished for 123 trap days between 10 May and 12 June 1991. Values differing significantly are denoted by ** ($p < 0.01$ as determined by pairwise *t*-tests of daily catches).

	Salmon		Whitefish	
	3 m net	Control	3 m net	Control
1991 May–June				
Sum (kg)	1 878	4 948	119	114
	**	**		
Calendar days	32	32	32	32
Mean/trap day (kg)	15.3	40.2	1.0	0.9
S.e.	1.8	3.9	0.2	0.3
Trap days	123	123	123	123

Table 3b. Total catch of Atlantic salmon and whitefish from five modified trapnets with a 3-m-deep prohibiting net in front of the wings and from five control trapnets. Each type of trap was fished for 102 trap days between 6 August and 26 August 1991. No significant differences were detected by pairwise *t*-tests of daily catches.

	Salmon		Whitefish	
	3 m net	Control	3 m net	Control
1991 August				
Sum (kg)	33	31	755	914
Calendar days	21	21	21	21
Mean/trap day (kg)	0.3	0.3	7.4	9.0
S.e.	0.1	0.1	1.0	1.3
Trap days	102	102	102	102

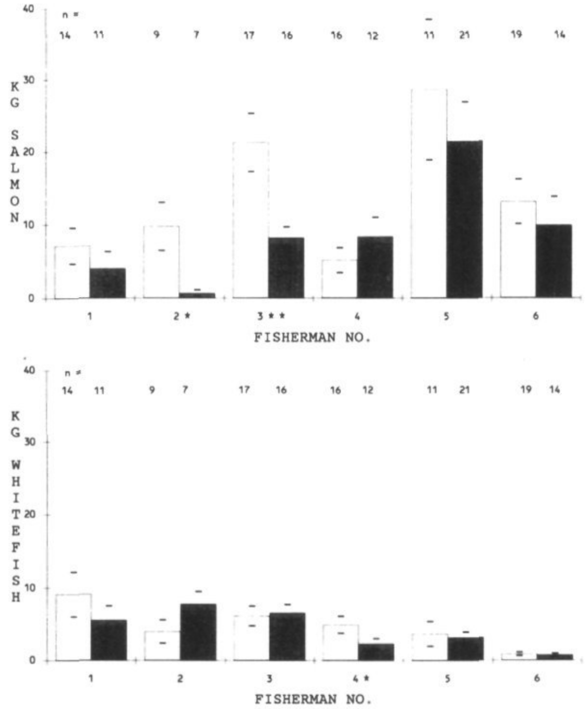

Figure 6. Mean daily catch (± s.e.) of salmon and whitefish. Fishermen fished with two trapnets each: one control net (white column) and one with ropes (Fig. 2) inside the last compartment (shaded column). Values differing significantly between trap types are denoted by * ($p < 0.05$) and ** ($p < 0.01$) as determined by pairwise *t*-tests of daily catches.

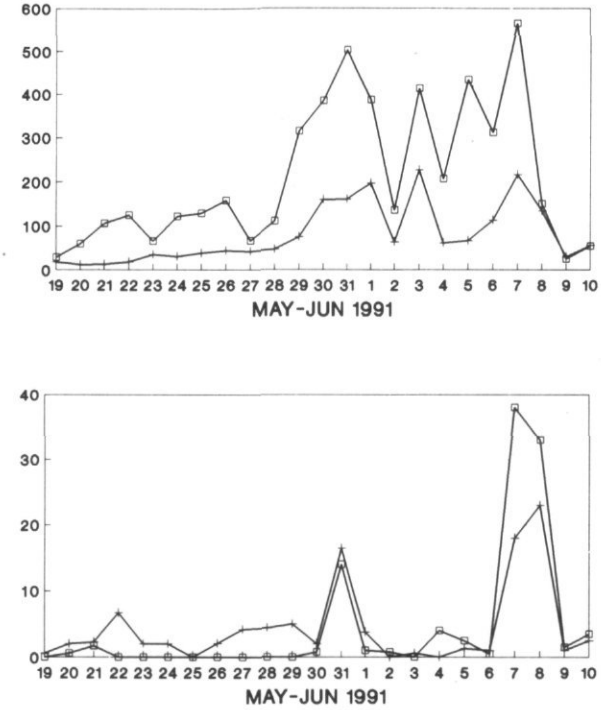

Figure 7. Daily catch of salmon (upper graph) and whitefish (lower graph) in six control trapnets (squares) and in six trapnets with prohibiting nets (crosses). Note differing vertical scales.

slightly northwards, towards the spawning rivers. Meanwhile, trapnet fishing for whitefish could continue.

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Appendix: Experiment trap location protocol

Table A1. Experiment with thin ropes inside the last compartment of trapnet.

Fisherman	Reference traps Coordinates	Dates	Modified traps Coordinates	Dates
1	63°40′15N 22°31′40E	2.6.–15.6.89	63°42′48N 22°31′9 E	5.6.–15.6.
2	63°42′7 N 22°33′0 E	6.6.–15.6.89	63°42′5 N 22°32′5 E	7.6.–15.6.
3	63°42′28N 22°31′80E	29.5.–15.6.89	63°43′34N 22°32′17E	29.5.–15.6.
4	63°40′8 N 22°30′5 E	29.5.–15.6.89	63°40′85N 22°30′0 E	3.6.–15.6.
5	63°51′2 N 22°36′8 E	5.6.–15.6.89	63°51′1 N 22°36′0 E	26.5.–15.6.
6	63°43′4 N 22°31′9 E	28.5.–15.6.89	63°43′6 N 22°29′4 E	2.6.–15.6.

Table A2. Experiment with large-meshed polyethylene panels in the front part of trapnet.

Material of the trapnet compartments	Dates	Hauls	Trap days	Coordinates
200 mm polyethylene	15.5.–11.7.90	52	57	63°34.7′N 22°19.4′E
150 mm polyethylene	24.5.–11.7.90	45	49	63°34.0′N 22°18.4′E
60 mm polyamide	1.6.–11.7.90	34	41	63°35.6′N 22°18.6′E
200 mm polyethylene	28.5.–12.7.91	42	46	63°34.7′N 22°19.4′E
80 mm & 250 mm polyethylene	12.6.–13.7.91	32	32	63°34.7′N 22°19.1′E
60 mm polyamide	15.5.–12.7.91	49	59	63°34.6′N 22°19.7′E
Total		254	284	

Table A3. Experiment with a prohibiting net in front of trapnet, spring and early summer.

Trapnet	Dates	Hauls	Trap days	Coordinates
1 Reference	7. –21.5.90	10	15	63°44.3′ N 22°32.4′ E
1	22.5.– 5.6.90	9	15	
2	7. –20.5.90	8	14	63°44.1′ N 22°32.0′ E
2 Reference	21.5.– 5.6.90	14	16	
6 Reference	19.5.– 9.6.91	18	22	63°40.15′N 22°31.40′E
7	26.5.– 9.6.91	10	15	63°40.37′N 22°31.40′E
8 Reference	29.5.– 9.6.91	10	12	63°42.43′N 22°32.75′E
9	25.5.– 9.6.91	14	16	63°43.0′ N 22°32.75′E
10 Reference	29.5.– 9.6.91	9	11	63°41.88′N 22°29.28′E
11	26.5.–10.6.91	11	16	63°41.18′N 22°32.13′E
12 Reference	10.5.–10.6.91	32	32	63°42.48′N 22°31.89′E
13	13.5.–10.6.91	29	29	63°43.27′N 22°31.77′E
14 Reference	27.5.–11.6.91	16	16	63°41.00′N 22°29.00′E
15	28.5.–11.6.91	15	15	63°41.00′N 22°28.30′E
16 Reference	11.5.–10.6.91	22	31	63°44.2′ N 22°32.1′ E
17	10.5.–12.5.91	27	34	63°44.4′ N 22°31.4′ E
Total		254	309	

Table A4. Experiment with a prohibiting net in front of trapnet, later in the summer.

Trapnet	Dates	Hauls	Trap days	Coordinates
3 Reference	21. –27.8.90	4	7	63°43.6′ N 22°31.4′ E
3	28.8.– 3.9.90	4	7	
4	21. –27.8.90	4	7	63°43.6′ N 22°31.0′ E
4 Reference	28.8.– 3.9.90	4	7	
6 Reference	6.8.–25.8.91	13	20	63°40.15′N 22°31.40′E
7	6.8.–25.8.91	13	20	63°40.37′N 22°31.40′E
8 Reference	6.8.–26.8.91	21	21	63°42.43′N 22°32.75′E
9	6.8.–26.8.91	21	21	63°43.0′ N 22°32.75′E
10 Reference	6.8.–24.8.91	13	19	63°41.88′N 22°29.28′E
11	6.8.–24.8.91	13	19	63°41.18′N 22°32.13′E
12 Reference	6.8.–26.8.91	21	21	63°42.48′N 22°31.89′E
13	6.8.–26.8.91	21	21	63°43.27′N 22°31.77′E
14 Reference	6.8.–26.8.91	20	21	63°41.00′N 22°29.00′E
15	6.8.–26.8.91	20	21	63°41.00′N 22°28.30′E
Total		192	232	

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Videotape documentation of salmon (*Salmo salar*) and whitefish (*Coregonus lavaretus*) reacting to a modified whitefish trapnet

Anna-Liisa Toivonen and Richard Hudd

Toivonen, A.-L., and Hudd, R. 1993. Videotape documentation of salmon (*Salmo salar*) and whitefish (*Coregonus lavaretus*) reacting to a modified whitefish trapnet. – ICES mar. Sci. Symp., 196: 59–61.

The behaviour of trapped fish inside a whitefish trapnet was documented with an underwater video camera to test whether the trap could be modified to selectively exclude Atlantic salmon (*Salmo salar* L.). The trapnet was modified and equipped with a cone of orange-coloured twine threads (1.7 mm diameter) tied from the end of the last funnel of the trap to the end of the last fish bag. The reaction of the fish to the modified threaded funnel section was videotaped. The camera was positioned beside the trap funnel so that behaviour could be observed as the fish either entered or avoided the fish bag. Videotape recordings were made for 24 h. The diurnal activity of the fish was also recorded, with the most active period being between 06.00 and 11.00. Species identification from the videotape record was difficult because of the very short time of an observation and because of the quality of the images. Of 104 observations made during the 24 h, 55 were estimated to be whitefish (*Coregonus lavaretus* s. str. L.), 28 salmon, and the species of the remaining 21 could not be identified.

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Introduction

The by-catch of Atlantic salmon in whitefish trapnets in Finland has increased from a level of 5% to over 50% in the last decade, according to the catch statistics of Finnish Game and Fisheries Research Institute. A method of modifying the trapnet to select whitefish and reject migrating adult salmon was tested. The catch statistics of an experiment with modified and reference trapnets are presented in an accompanying article (Toivonen and Hudd, 1993). To observe the behaviour of the fish near and inside the modified gear, a videotape was made to see whether the modification was effective and species selective. Diurnal activity of fish was also recorded and observed. Videotape technology has been used in fish behavioural studies (Arimoto and Inoue, 1985) and studies of gear technology (Twohig and Smolowitz, 1984; Suuronen, 1991).

Materials and methods

A video camera was placed inside the fish bag of a whitefish trapnet beside the end of the innermost funnel. The funnel was equipped with a cone of orange-coloured twine threads (1.7 mm diameter) that would show up clearly in the videotape. The threads were about 10 cm apart from one another and conically joined tautly to the rear of the fish bag. To enter the fish bag, the fish had to swim through the threads. The camera was horizontally focused on the end of the funnel and mounted at about 1.5 m distance. The camera used was a Philips 402 with autoiris, focal length 3.8 mm, 122° horizontal angle of view and minimum illumination level of 0.97 lux. The waterproof chamber housing the camera was painted black. Black-and-white VHS videotape was used in a Salora SV7400 videotape recorder operating in normal (24 h) mode.

The site of the experiment was in the southern Bothnian Bay (Baltic Sea). Recordings were made between 23.40 on 3 July and 23.15 on 4 July 1989. At this time of year at this latitude, the sun is up from 03.30 to 23.30. No artificial illumination was used. During the darkest hours, between 01.00 and 03.00, it was very difficult to make any observations. The weather was typically cloudy in the morning but cleared by approximately 09.00. Wind velocity was 6–8 m s^{-1} from the WSW.

Seawater transparency varied from less than 1 m to approximately 3 m. There is no tide in the Bothnian Bay.

The videotapes were analysed for species identification and fish behaviour. Times of observations were recorded. The identification of species was at times difficult because of the relatively short time each fish was visible on the tape and because lighting conditions varied throughout the 24 h recording period.

Table 1. Recorded observations on the videotape.

	No. of all observations	No. entering trap	No. turning away	No. of attempts before entering
Salmon	28	10	17	1.7
Whitefish	55	21	16	0.8
Unidentified	21	5	10	

Results

The videotape record documented 104 fish observed. (Small fish such as herring (*Clupea harengus*) or three-spined stickleback (*Gasterosteus aculeatus*) were not counted, although many of them were observed throughout the tapes.) Among these observations, 36 fish passed through the threaded funnel of the trap and entered the fish bag of the trapnet. Species composition of the 104 fish observed was estimated to be 55 whitefish, 28 salmon, and 21 unidentifiable fish (Table 1).

Pronounced diurnal activity was observed (Fig. 1). The frequency distribution of all observations shows a pronounced peak between 9.00 and 11.00, whereas between 5.00 and 6.00 for example, only one observation was documented. The frequency distribution of salmon observations strongly correlates with all observations (Pearson correlation coefficient r = 0.87), whereas the whitefish observations only correlate markedly (r = 0.60). Both the Pearson chi-square test (p = 0.001) and Fisher's Exact Test (p < 0.001) indicate a difference in the hourly distribution of the observations of the two species.

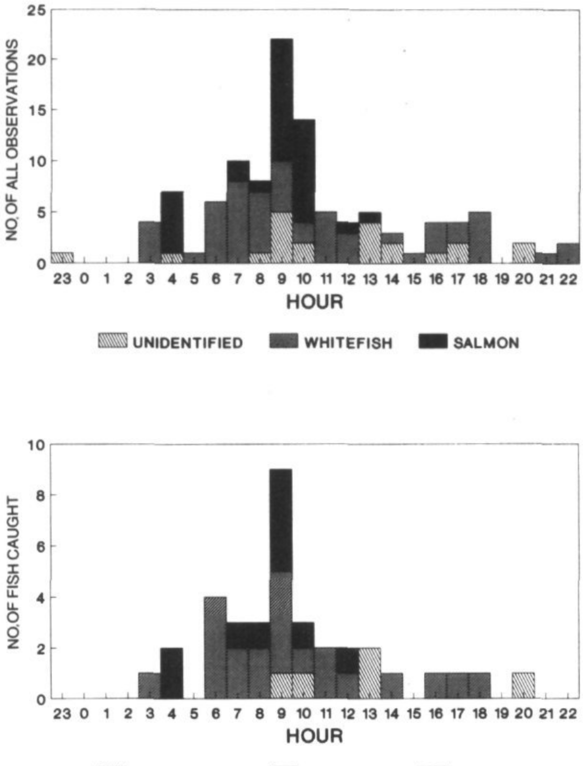

Figure 1. Diurnal distribution of (upper) all observations and (lower) fish caught in a trapnet fish bag, determined from videotape records made inside the fish bag between 23.40 3 July and 23.15 4 July 1989. Each column represents one hour, e.g. that labelled 10 depicts observations documented between 10.00 and 10.59. Note differing vertical scales.

The observed behaviour was classified as (a) entering the fish bag, (b) turning back before the threads, or (c) other. Most of the "other" observations were fish that were already inside the fish bag swimming past the camera. The same fish could have appeared several times on the videotape. Differences in behaviour of the two species, i.e. whether they either turned back or swam through the threads, were tested with the Pearson chi-square. The probability of the difference being caused by chance alone was more than 12% (p = 0.122).

Discussion

Whitefish, being resident at the time, entered the fish bag more evenly through the day than salmon, which were migratory. The relatively short diurnal occurrence of salmon may have been caused by a school of salmon passing the site at that time of day. The most active time inside the gear was between 06.00 and 11.00. The peak was clearly after 09.00. Fishermen ordinarily empty the fish bags each day between 06.00 and 09.00. By doing so they may be disturbing the peak entrance of fish into the trap.

By using video to observe fish and their behaviour when they are about to enter the fish bag, we have a unique way to discover the efficiency of the gear modification. Salmon make on average 1.7 attempts before they enter the fish bag, whereas whitefish enter on average more often than they turn back. The observations made of unidentified fish, if identified, could change the ratio. However, based on the data, the conclusion that there is a difference in the behaviour of these two species in their reaction to the threads is not statistically warranted (p > 0.12).

The circumstances in the site during the experiment were relatively good. Calmer weather would have improved the quality of the video. On the other hand it might have decreased the catch of the trapnet. A longer surveillance period and a more light-sensitive camera would have increased the number of observations also during the dark hours and eased the identification of species.

For further investigations of salmon and whitefish in trapnets, it is helpful to know when the fish are active and enter the gear, so that experiments can be designed to take place during the most active hours.

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ICES mar. Sci. Symp., 196: 62–67. 1993

The influence of seismic exploration with airguns on cod (*Gadus morhua*) behaviour and catch rates

Svein Løkkeborg and Aud Vold Soldal

Løkkeborg, S., and Soldal, A. V. 1993. The influence of seismic exploration with airguns on cod (*Gadus morhua*) behaviour and catch rates. – ICES mar. Sci. Symp., 196: 62–67.

Analyses of catch records showed that geophysical activity with airguns significantly influenced the catch rates of cod (*Gadus morhua*) in long-line and trawl fisheries. Catch reductions of 55–80% were observed for long lines set within a seismic survey area, and the by-catch of cod in shrimp trawl was reduced by about 80–85%. The by-catch of cod in trawl fishery for saithe, however, was observed to increase threefold and to return to normal immediately after the seismic work ended. The predominant frequencies of airgun sound spectra match the most sensitive auditory band of cod. The reductions in catch rates are undoubtedly due to behavioural responses of cod to airgun sound. The fish probably avoided the approaching geophysical vessel by swimming away from the sound source, and the amount of fish available to any fishing gear used in this area was thereby reduced. The results from the trawl fishery for saithe were explained by the short duration of the sound emissions during this particular seismic survey.

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Introduction

Geophysical surveys have been conducted continuously in the North Sea for about 30 years. During the last few years, seismic survey vessels have also been operating on fishing grounds in the Norwegian Sea and in the Barents Sea. Concern has been expressed by fishermen that sounds generated by acoustic survey devices affect commercial fishing. In particular, Norwegian fishermen using long line or trawl have reported significantly reduced catch rates caused by the operations of seismic vessels.

Fish detect and respond to sounds (Tavolga *et al.*, 1981; Hawkins, 1986), and airgun discharges have been reported as eliciting startle and alarm responses in rockfish (*Sebastes* spp.) (Pearson *et al.*, 1992). Changes in the depth distribution of whiting (*Merlangius merlangus*) upon discharges of a single airgun have been reported (Chapman and Hawkins, 1969), and a field study suggested changes in fish distribution along the tracklines of a seismic survey vessel (Dalen and Raknes, 1985). In hook and line fishing, the catch rate of rockfish was observed to decline by 50% during sound emission from a single airgun (Skalski *et al.*, 1992). However, the quantitative effects of seismic survey operations on catch success in commercial long-lining and trawling have not been documented.

The present study is based on catch data obtained from long-liners and trawlers fishing in areas where seismic survey operations were being conducted. Catch rates of cod (*Gadus morhua*) obtained within and at various distances from a seismic survey area were compared. The duration of the effect of seismic operations was also investigated.

Materials and methods

Long-lining

In January 1990, a seismic survey was carried out off the coast of Finnmark (northern Norway) in an area in which several long-liners were fishing for cod. The seismic vessel used an array of four sleeve guns (chamber volume 40 in^3). The survey tracklines were about 4700 m long, and the guns were discharged every 12.5 m (i.e. at intervals of about 5 s). A total of 32 tracklines were run during four periods (Table 1). Catch data were obtained from four autoliners ("Husby",

Table 1. Schedule of the seismic survey conducted off the coast of Finnmark (northern Norway) in 1990.

Period	Start sound emission		End sound emission		No. of survey tracklines
	Date	Time	Date	Time	
1	19 Jan	18.32	20 Jan	04.33	7
2	21 Jan	16.43	22 Jan	06.38	10
3	28 Jan	09.14	28 Jan	12.00	3
4	29 Jan	03.44	29 Jan	20.27	12

"Førde", "Frøyanes", and "Værland"). For each fleet of long lines, the skipper normally notes the position, time of setting, and estimates the weight of the catch. These notes were related to the positions of the survey tracklines and the times of discharges of the guns.

Trawling

The effects of seismic operations on the by-catch of cod above legal size (>42 cm) in trawl fisheries for shrimp (two cases) and saithe (one case) were studied. With the permission of the shipowner, catch data were obtained from the official catch records required and stored by the Norwegian authorities. The estimated weight of the catch, and the time and start position of each haul, were noted and related to the positions and times of running of the geophysical survey tracklines. As the catch records only give the start position of each haul, and not the towing direction or stop position, it is not possible to calculate the exact distance between the survey tracklines and the trawl haul. Each trawl haul is usually between 10 and 15 nautical miles long. In these analyses, hauls starting closer than 5 nautical miles from the seismic tracklines are considered to have been influenced by the airgun noise. Variance analyses (General Linear Models, SAS Institute Inc., Cary, IN) were used to test differences between catch rates before, during and after seismic activity.

The following cases were analysed:

1. A geophysical survey conducted off the coast of Finnmark, northern Norway, in June 1989. The seismic source used was an array of 20 sleeve guns each with a chamber volume of 40 in^3. Shot interval was 25 m. A shrimp trawler was fishing within and close to the survey area (bottom depth 200–300 m) several weeks before and for two days during the seismic activity. Catch data from hauls taken before and during the airgun activity were compared.
2. A survey conducted in the Barents Sea east of Bear Island in August 1991. The seismic vessel used an array of 40 airguns with a total volume of 2660 in^3 and a shot interval of 25 m. A shrimp trawler, fishing within the Bear Island area at 200 to 300 m depth for several weeks, was trawling closer than 5 nautical miles from the geophysical vessel for three days. Catch records from before, during, and after the seismic activity were compared.
3. A survey conducted at Storegga of the coast of Møre (western Norway) in April 1991. An extensive shooting programme (1600 km) was planned, but only 9 h of shooting on 18 April and 3 h on 14 April (a total of 98 km) were conducted owing to rough weather con-

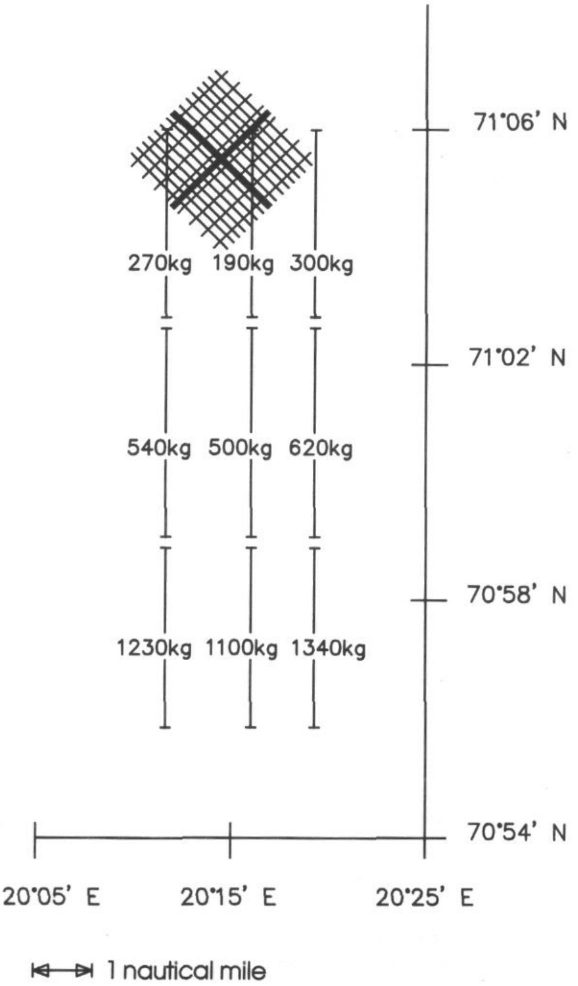

Figure 1. Tracklines of the geophysical survey carried out off the coast of Finnmark in 1990. Locations and catch rates of the fleets of "Husby" are shown.

ditions. The airgun array used had a chamber volume of $4800\ \mathrm{in}^3$ and the shot interval was 25 m. The by-catch of cod in the bottom trawl fishery for saithe (150–250 m bottom depth) was analysed from four trawlers fishing in the survey area before, during, and after the geophysical activity.

Results

Long-lining

Figure 1 shows the locations and catch rates of the fleets of "Husby" that were soaked on 28 and 29 January when the seismic vessel was operating. However, the exact time of setting was not noted by the skipper. Three fleets of lines were set 5–8 nautical miles from the survey area, and their mean catch rate was 1223 kg cod. The fleets set 1–5 nautical miles from the survey area caught on average 553 kg, and the fleets set within the area caught 253 kg. These catch rates are 45 and 21%, respectively, of that of the fleets set furthest away from the survey area.

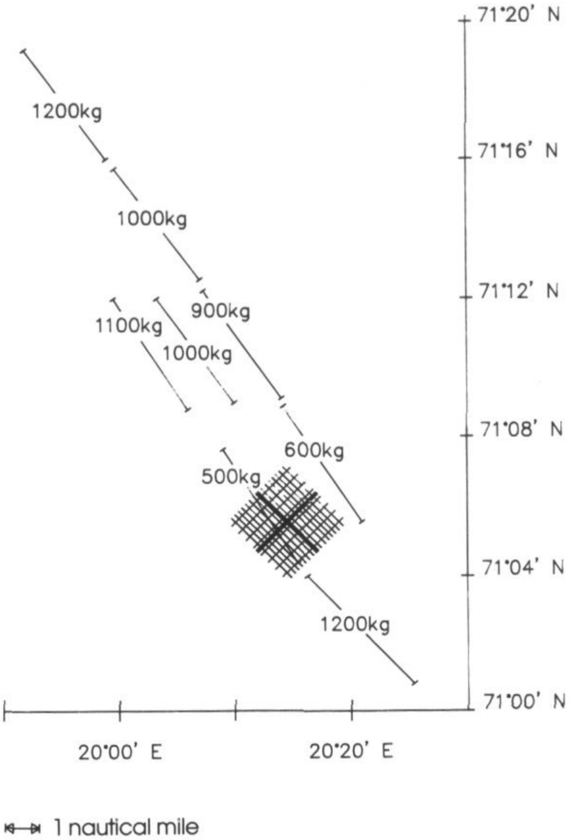

Figure 2. Tracklines of the geophysical survey carried out off the coast of Finnmark in 1990. Locations and catch rates of the fleets of "Førde" are shown.

Table 2. Distance from the seismic survey area, time of setting relative to sound emissions and catch rate of long-line fleets of the autoliners "Førde" and "Frøyanes". Distance from survey area is the distance (in nautical miles) between each end of the fleet and the nearest survey trackline. Elapsed time is the time that elapsed between the ending of sound emissions and setting of fleets. Fleets 11–15 of "Frøyanes" are related to period 2 (see Table 1), the other fleets are related to period 1.

Vessel	Distance from survey area	Elapsed time	Catch rate (kg/fleet)
"Førde"			
Fleet 1	6.5–2.6	During[a]	1100
Fleet 2	0.7–4.1	During[a]	1000
Fleet 3	0.7–4.1	6 h 30 min	1200
Fleet 4	0–1.2	7 h 10 min	500
Fleet 5	0.8–1.8	24 h 40 min	600
Fleet 6	2.0–5.3	25 h 20 min	900
Fleet 7	5.7–9.7	25 h 50 min	1000
Fleet 8	9.9–13.7	26 h 20 min	1200
"Frøyanes"			
Fleet 1	5.1–7.2	Before[b]	2500
Fleet 2	6.1–8.3	Before[b]	2000
Fleet 3	4.1–6.7	Before[b]	2800
Fleet 4	6.7–8.4	Before[b]	2700
Fleet 5	3.4–5.9	−4 h 20 min[c]	1800
Fleet 6	6.2–7.9	During[a]	1600
Fleet 7	2.0–5.7	1 h 50 min	1900
Fleet 8	5.0–7.2	9 h 45 min	1300
Fleet 9	1.5–6.3	17 h 5 min	1300
Fleet 10	3.3–6.5	24 h 35 min	2200
Fleet 11	2.3–5.0	−4 h 40 min[c]	1200
Fleet 12	4.4–6.5	During[a]	1300
Fleet 13	5.5–6.6	During[a]	1500
Fleet 14	6.7–7.2	3 h 30 min	1400
Fleet 15	7.3–8.2	10 h 25 min	1200

[a] The fleet was set during sound emissions.

[b] The fleet was set and hauled before sound emissions started.

[c] Time between setting of fleet and starting of sound emissions. The soak times for these fleets were about 9 h.

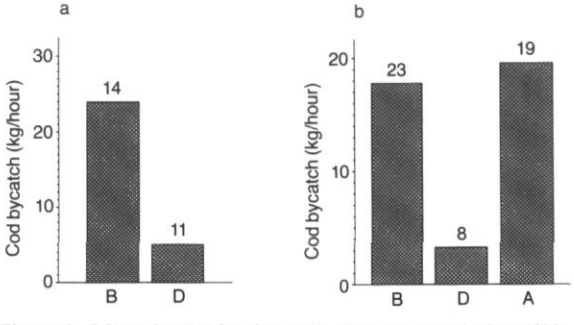

Figure 3. Mean by-catch of cod in shrimp trawl before (B), during (D) and more than 24 h after (A) airgun activity conducted within 5 nautical miles range from the trawler. (a) Off the coast of Finnmark. (b) In the Barents Sea east of Bear Island. Numbers of hauls are given atop each column. Note differing vertical scales.

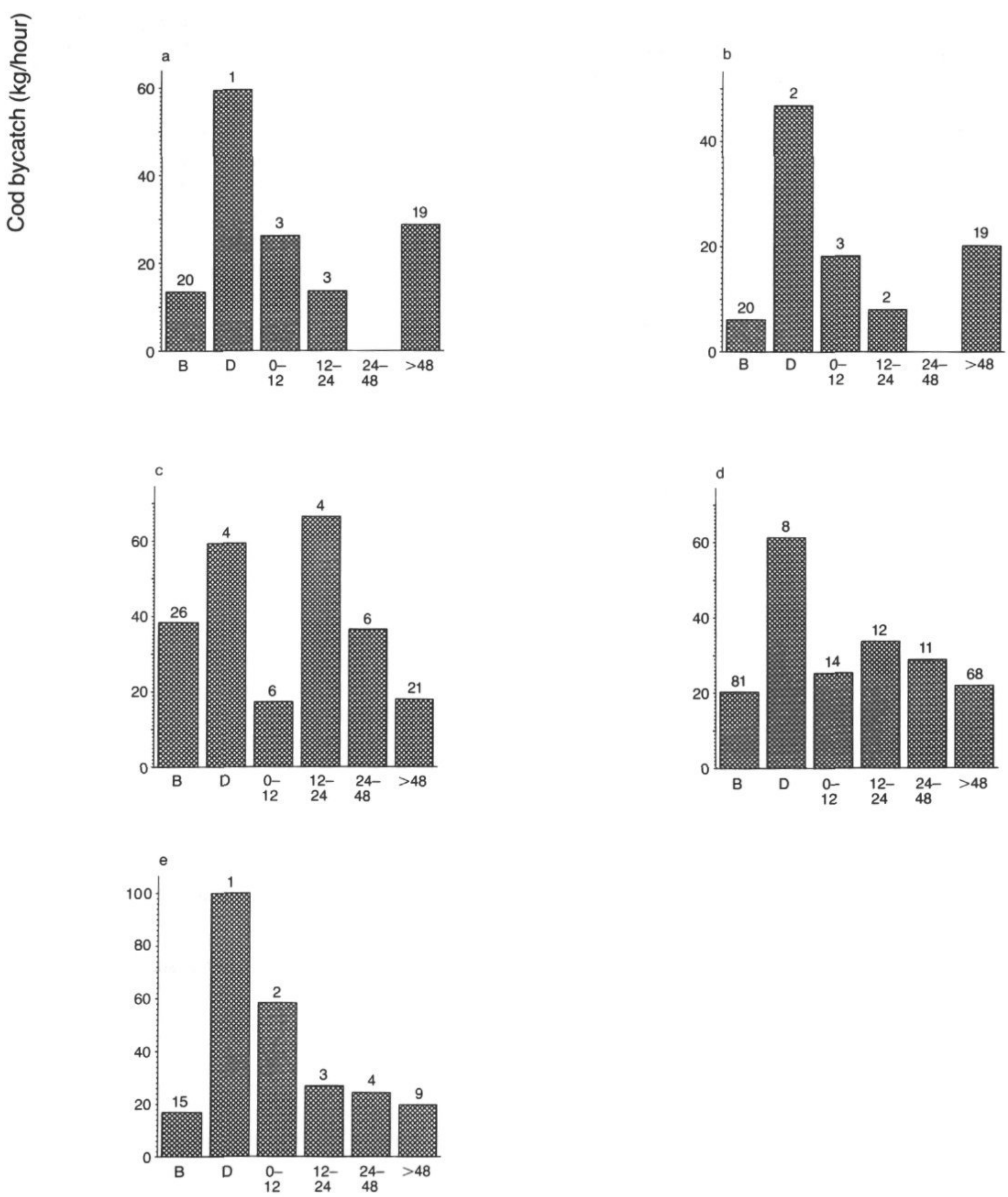

Figure 4. Mean by-catch of cod in bottom trawling for saithe off the coast of Møre before (B), during (D) and at different time intervals (values in hours) after airgun activity. (a) to (d) are four different fishing vessels, and (e) the average of these vessels. Number of hauls are given atop each column. Note differing vertical scales.

The catch data for "Førde" are shown in Table 2 and Figure 2. Fleets 1 and 2 were set during sound emissions, and fleets 3 and 4 about 7 h after sound emissions ended. The catch rate of fleet 4, which was set within the seismic survey area, was 45% of the mean catch rate of fleets 1–3, which were set about 1–6 nautical miles from this area. Fleets 5–8 were set about 24 h after sound emissions ended, and at increasing distances from the survey area. The catch rates for these fleets increased with increasing distance from the survey area.

The fleets of "Frøyanes" were all set about 1.5–8.5 nautical miles from the seismic survey area (Table 2). The fleets soaked prior to sound emissions caught 2000–2800 kg cod each (mean = 2500 kg). Fleets set during sound emissions and within 24 h after emissions ended caught 1200–2200 kg (mean = 1518 kg), which indicates a catch reduction of about 40%.

The notes obtained from the "Værland" give the total catch for each day of fishing and not for each fleet. The catches for 15 to 19 January ranged from 6300 to 8250 kg (mean = 7100 kg), whereas 4000 kg were caught 20 January (sound emissions started at 18.32 on 19 January, Table 1). On 21 January this vessel changed fishing ground.

Trawling

By-catches of cod in shrimp trawls were significantly ($p < 0.05$) reduced during airgun activity in both areas investigated. When shooting started, cod catches decreased from an average of 24 kg per towing hour to 5 kg per hour (79% reduction) off Finnmark (Fig. 3a). In the Bear Island area, the by-catch of cod decreased from an average of 18 kg per towing hour to 3 kg per hour (83% reduction; Fig. 3b), when the seismic vessel started shooting in the trawling area (less than 5 nautical miles from the trawler). In the Bear Island area, catches of cod increased to pre-shooting levels about one day after shooting ended.

For the trawlers operating at Storegga a threefold increase in cod catches was found when the short airgun activity sequences were conducted. The catches were significantly higher during shooting than before and at different time intervals after shooting ($p < 0.05$; Fig. 4a–e). When sound emission ended, the catches returned to pre-shooting levels within about 12 h. The number of hauls taken during shooting, however, was low owing to the short shooting period.

Discussion

Fish are known to hear and react to sounds (Hawkins, 1986), and the results obtained in the present study demonstrate that cod respond to sounds from airgun arrays. The airguns normally used for offshore geophysical exploration produce low-frequency sounds with maximum energy levels from below 10 to a few hundred Hz (Malme *et al.*, 1986), which match well the most sensitive frequency band of cod (Chapman and Hawkins, 1973).

Fish may react to sound in different ways. Cod have been observed to avoid an approaching sound source (vessel) with a calm swimming movement horizontally and vertically (Olsen *et al.*, 1982; Engås *et al.*, 1991a, b; Ona and Godø, 1990). It has also been suggested that demersal fish such as cod dive and stay nearly immobile on the seabed when scared by noise (Dalen and Raknes, 1985). Thus, when responding to sounds from airguns, the fish may either leave the survey area or stay within the area close to the bottom. The results obtained in this study support the former explanation as both long-line and trawl catches were shown to decrease during sound emission. If the fish remained in the area close to the bottom, they should have become more available for the shrimp trawl which is designed to maintain close contact with the seabed.

However, the by-catch of cod in the trawl fishery for saithe showed a threefold increase during airgun shooting. What was unusual about this case was the short duration of the shooting sequences owing to bad weather conditions. If fish start to avoid the sound source by diagonal downwards movements, the concentration of fish will temporarily increase at the bottom close to the survey tracklines as the fish move out of the survey area. This "plough effect" is probably of short duration, and a trawler fishing close to the tracklines when the seismic vessel starts shooting may, for a short time, make larger catches.

The present catch data were obtained from commercial fishing vessels that happened to be operating on fishing grounds where seismic explorations were being conducted. These data therefore do not provide an ideal basis for quantifying catch reductions caused by seismic survey operations or for investigating the spatial and temporal extent of the effects of such operations. However, although uneven fish distribution may cause significant differences among catches obtained from the same fishing ground, the catch data investigated in this study, with one exception, showed the same tendency. These data therefore demonstrate significant catch reductions during airgun discharges, and indicate that effects lasted for 24 h and were at least 9 km in extent. However, to obtain more exact data on the effects of seismic operation on catch rates, a controlled experiment should be conducted.

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Behavioural reactions of demersal fish to bottom trawls at various light conditions

Stephen J. Walsh and William M. Hickey

Walsh, S. J., and Hickey, W. M. 1993. Behavioural reactions of demersal fish to bottom trawls at various light conditions. – ICES mar. Sci. Symp., 196: 68–76.

Comparisons of the behaviour of demersal roundfish and flatfish towards a bottom trawl were made during light and dark conditions, as well as in dark conditions with constant artificial light introduced. Observations of fish orientation and swimming behaviour were recorded from 123 still photographs and 8 h of video recording taken by a camera attached to an underwater remotely operated vehicle. The results of the analysis show that, at low light levels ($<10^{-4}$ lux), the ordered pattern of reaction behaviour seen in roundfish during high light intensities ceases. The attachment of artificial light ($>10^{-4}$ lux) to the footgear, at night, was insufficient to stimulate fish to react in the ordered way. Flatfish generally do not orientate themselves to the general direction of the tow, and show little difference in day and night reactions to the trawl. At night, in the absence of light, there is no ordered orientation to the trawl and there is a lower activity level, in response either to lower light intensity or to endogenous diel rhythms.

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Introduction

The use of scuba diving, remotely operated underwater vehicles, and photographic techniques has contributed significantly to our understanding of fish behaviour patterns in the fishing zone of trawls extending from the doors to the codend [see Ben-Tuvia and Dickson (1969) and Wardle (1983, 1986, 1987) for excellent reviews]. Behaviour of fish is governed by endogenous factors and by external physical factors, such as illumination, water transparency and temperature, and by visual and tactile responses to design and riggings of the trawl. Investigations in the 1960s showed that during daylight, fish were orientated in front of the trawl in the direction of the tow, whereas, at night, this orientation was less marked (Parrish *et al.*, 1962; Blaxter *et al.*, 1964). Continuing research led to conflicting results about orientation of some fish species at night (Beamish, 1969; Parrish *et al.*, 1969), and non-visual senses such as detection of sound or hydrodynamic pressure disturbances were often cited as being responsible for night-time reaction patterns to the gear.

Recently, research has demonstrated that at low light intensities, below the threshold value of a fish's vision ($<10^{-6}$ lux), fish showed none of the recognizable ordered patterns of reaction to or avoidance of groundgear as seen during daylight until the fish were within centimetres of collision with the gear (Wardle, 1986; Glass and Wardle, 1989). These authors suggested that the "low" light in earlier experiments was not precisely measured and that dinoflagellate bioluminescence, activated by turbulence near the net, was not considered. Several studies have discussed the potential of bioluminescent light in allowing fish to detect and react to a towed net (Parrish, 1969; Chestnoi, 1971; Kelly and Tett, 1978; Wardle, 1986; Glass *et al.*, 1986; Glass and Wardle, 1989). Glass and Wardle (1989) concluded that at light intensities below a fish's threshold vision, fish showed no ordered pattern of behaviour because of the lack of optomotor reactions normally associated with visual images. They further concluded that non-visual senses in the absence of vision do not produce the ordered behaviour reaction pattern and that fish reacted to the gear only when it collided with them.

The aim of this study was to test the no-ordered-reaction hypothesis by comparing the orientation and swimming behaviour of various fish species at low light levels ($<10^{-4}$ lux) and at levels ($>10^{-4}$ lux) induced by artificial light during night tows. Behaviour of the different fish species was measured during daylight (>1 lux) to serve as a baseline description of ordered patterns of reaction to the trawl.

Material and methods

Experiments were conducted on board the research vessel "Lady Hammond" on the Scotian Shelf, Nova Scotia, in October 1990. A total of seven fishing tows (two day and five night), using a bottom trawl equipped with rockhopper footgear, were made during which 8 h of video observations of net and fish were recorded and 661 35 mm photographs were taken. A similar experiment carried out in March 1990 yielded preliminary results but these were not included because of the small number of observations on roundfish, although flatfish were abundant.

Video and still camera observations were recorded for cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), American plaice (*Hippoglossoides platessoides*), yellowtail flounder (*Limanda ferruginea*), winter flounder (*Pleuronectes americanus*), pollock (*Pollachius virens*), silver hake (*Merluccius bilinearis*) and skate (*Raja* sp.) found in the mouth area of the trawl. The average towing speed was 3.5 knots over a 44 to 53-m bottom depth range, with an average bottom temperature of 8°C. Tows were made around mid-day and late in the evening with an average tow duration of 1 h. An underwater remotely operated vehicle (ROV) equipped with an Osprey OE1321 SIT (video) camera (with a measured sensitivity down to 10^{-4} lux) was moved into position ahead of the wing quarter, to look across the mouth area of the footgear. A Photosea 2000-35 mm still camera (400 frames) was mounted alongside the video camera and flash photographs were taken by the operator on the bridge.

Observation techniques followed closely those outlined by Glass and Wardle's (1989) experiments. At night, the ROV's single QL-3000 quartz halogen lamp (250 W output) was switched on in order to move the ROV into position. After positioning, the floodlight and shiplights were extinguished and all ROV's LEDs were covered. Periodically, to check the ROV for position, the floodlight was turned on and then off. A 2 min interval elapsed before the next series of photographs were taken; photos were spaced at 20–30 s intervals.

Experimental protocol

Because no underwater light meter was available, no measurements of light intensity or bioluminescence were taken. The only estimate of light intensity available was the sensitivity threshold of the SIT camera on the ROV. We compensated for lack of light measurements by designing the experiments based on two *a priori* null hypotheses. The first null hypothesis was that there is no difference in the reaction behaviour of fish to the trawl between night and day. The alternate hypothesis stated that absence or presence of the characteristic ordered daylight behaviour pattern indicates that light levels are below or above the threshold value of fish vision (10^{-6} lux). The second null hypothesis was that at night, the introduction of a constant supply of artificial light ($>10^{-4}$ lux) on the footgear should result in fish exhibiting the ordered pattern of behaviour. The alternate hypothesis stated that artificial light ($>10^{-4}$ lux) introduced in an ambient environment of $<10^{-4}$ lux would not result in fish exhibiting the ordered pattern of behaviour like that seen during daylight.

Artificial light was created during one night haul by tying 11 × 15.3 cm Cyalume plastic chemical lightsticks (American Cyanamid Co.) at 2 m intervals along the entire fishing line of the rockhopper footgear. The lightsticks were activated on deck just prior to shooting the trawl. Each lightstick gives off a light intensity of 34 lux 15 min after activation, which gradually reduces to 23 lux after 1 h (manufacturer's fact sheet).

Observations on fish reactions were assessed from 661 still photographs, 123 of which showed fish and a section of the footgear. Fish were identified and direction of orientation to the mouth of the footgear was recorded as an arbitrary compass direction (N, NE, NW, E, W, S, SE, SW), with north (N) representing the direction of the tow. Swimming behaviour of each fish was categorized according to body configuration as: (1) body in a glide or flexed shape indicating regular or cruising behaviour; (2) body in U- or S-shape indicating fast burst characteristic of startle behaviour; (3) resting on bottom; and (4) unknown, i.e. body shape unidentifiable. The number of collisions of fish with the footgear was also counted. The three flatfish species were treated as one group because they exhibited similar behavioural reactions and in many cases were difficult to separate. A separate category for all unidentifiable roundfish was used in the analysis. The number of observations of skate in the photographs was too low for orientation and swimming behaviour to be calculated.

Results

Trawl catches (kg)

The average catches of cod and haddock were higher during the daylight fishing hauls than at night, whereas average catches of flatfish, pollock, silver hake, and other species were higher at night (Table 1). During the single night haul with the lightsticks attached, catches were similar to the average catches of regular night hauls.

Table 1. Comparison of fishing catches (kg) of various species during daylight (3 hauls), dark (3 hauls), and artificial light (1 haul).

	Day			Night			Artificial light
Species	Total catch (kg)	Mean	s.d.	Total catch (kg)	Mean	s.d.	Total catch (kg)
Cod	583	194.3	90.7	357	119.0	146.4	121
Haddock	2288	762.7	501.4	878	292.7	293.1	253
Flatfish	97	32.3	20.5	195.5	65.2	83.7	92
Pollock	4	1.3	2.3	10.3	3.4	5.7	1
Hake	194	91.0	128.7	647	215.7	370.9	198
Other fish	152	50.7	26.6	209	69.7	88.1	46
Total	3318	1659	1171	2296.8	765.6	987.7	711

Day – high light intensity

Of the individual fish recorded on the still photographs, 96% were shown swimming ahead of the net in the same direction as the tow (N), with only 3% swimming at an angle (NE) (Table 2). A pronounced ordered pattern of behaviour was clearly identifiable (Fig. 1). Over 90% of cod, haddock, pollock, and unknown roundfish were showing cruising behaviour in front of the net; startle behaviour (<10%) was minimal (Table 3). Cod generally were located close to the bottom, ahead of the net, whereas haddock were generally higher off bottom by comparison and occasionally some were pictured turning back towards the net. No roundfish were seen resting on the seabed. The number of photographic observations of hake and flatfish was too low (<5 fish) to make any meaningful observations about swimming behaviour. However, video observations showed flatfish, ahead of the trawl, resting on the seabed and reacting to the footgear at distances of about 0.5–1 m. They generally moved a short distance in a lateral direction towards the opposite side of the trawl, settled on the bottom, and repeated the behaviour again when the footgear was near by, until they were either caught or escaped underneath the footgear.

Table 2. Orientation to direction of tow (North) and swimming behaviour of various fish species during fishing hauls conducted during daylight, dark, and artificial light.

Time	Direction	Total nos.	Cruising swimming (%)	Startled swimming (%)	Resting on bottom (%)	Behaviour unknown (%)	Total (%)
Day	North	288	94	5	1	0	96
	Northeast	10	80	10	10	0	3
	South	1	100	0	0	0	1
Total		299	94	5	1	0	100
Night	North	87	70	21	5	5	59
	Northeast	20	45	30	20	5	14
	Northwest	6	100	0	0	0	4
	East	6	66	17	17	0	4
	West	8	75	13	12	0	6
	Southwest	4	25	50	0	25	3
	South	14	64	14	8	14	10
Total		145	66	21	7	6	100
Artificial light	North	48	83	10	2	5	63
	Northeast	6	83	17	0	0	8
	Northwest	10	70	20	10	0	13
	East	1	100	0	0	0	1
	West	6	50	50	0	0	8
	South	5	40	0	20	40	7
Total		76	76	15	4	5	100

Figure 1. Cod and haddock showing the ordered reaction pattern to the trawl (out of photo at far right) during daylight. Fish are swimming forward in the direction of the tow.

Night – low light intensity

The number of fish seen in individual photographs was considerably lower than in daylight, with only 5 out of 67 photographs showing 6 or more fish (the largest number was 7), in contrast to 22 out of 26 photographs during daylight. Fifty-nine per cent (59%) of individual fish observations showed fish swimming in the direction of the tow (N), while 18% were orientated at an angle (NE and NW) (Table 2). Considered collectively, 84% of the 61 night photographs, depicting more than one fish, showed fish to be randomly orientated to the net. The recognizable ordered daylight pattern of behaviour was absent (Figs. 2 and 3). Many fish, including cod, haddock, flatfish, and unidentified roundfish, were seen on or close to the bottom. Many were close to the footgear or swimming in random directions. Four out of the 67 photographs showed collisions of the fish with the footgear (Fig. 4). The number of fish showing startle behaviour was higher at night (21%) than during the daylight (5%) and included haddock, flatfish, and unidentified roundfish (Tables 2 and 3). The numbers of pollock and hake were too low to reveal day and night differences in swimming behaviour. When the ROV's halogen lamp was activated, several round and flatfish species were seen resting on or close to the bottom and were slow to react to the approaching footgear. Reaction distances appeared to be less than 2 m and reaction occurred in random directions.

Night – artificial light

Again, the number of fish observed in the photographs was less than in daylight observations, with only 1 out of 30 photographs containing 6 fish. Sixty-three per cent of the individual fish were orientated to the direction of tow (N), while another 24% were orientated at an angle (NE and NW) (Table 2). However, 70% of the 30 photographs that showed more than one fish collectively showed random orientation of fish to the net, and several fish were very near to the footgear. The ordered reaction pattern was again absent (Figs. 5 and 6). One of the 30 photographs showed a skate in collision with the footgear.

The number of fish showing startle behaviour (5% day; 21% night; 15% artificial light) was again higher than in daylight but lower than at night-time (Table 2). Several flatfish and unidentified roundfish were ob-

Table 3. Comparison, by species, of orientation to the direction of the tow (north, northeast, and northwest combined) and swimming behaviour. Unidentifiable swimming behaviour and other orientations are not included.

Species	Time	No. obs.	Direction of tow (N, NE, NW) (%)	Cruising swimming (%)	Startled swimming (%)	Resting on bottom (%)
Cod	Day	26	100	100	0	0
	Night	18	67	39	12	6
	Night/Light	5	20	20	0	0
Haddock	Day	128	99	90	8	0
	Night	75	87	65	20	3
	Night/Light	13	92	69	15	0
Flatfish[a]	Day	5	20	0	20	80
	Night	19	32	21	5	16
	Night/Light	6	17	17	17	17
Pollock	Day[b]	27	100	93	7	0
Hake	Day	2	100	50	50	0
	Night	13	100	92	8	0
	Night/Light	25	96	92	4	0
Unknown roundfish	Day	111	100	100	0	0
	Night	23	39	4	17	17
	Night/Light	27	78	59	7	8

[a] Only north was considered for orientation to direction of tow because flatfish generally moved in a lateral direction in response to the approaching footgear.

[b] Pollock were not identified at other times.

served resting on the sea bottom (Table 3). Although the number of photographic observations of cod and haddock was lower and the numbers of hake and unidentified roundfish higher than during the two other sampling periods, there was a general trend to observe less startle behaviour and more cruising behaviour. However, the percentage of startle behaviour, with the exception of cod, was higher than during daylight observations (Table 3).

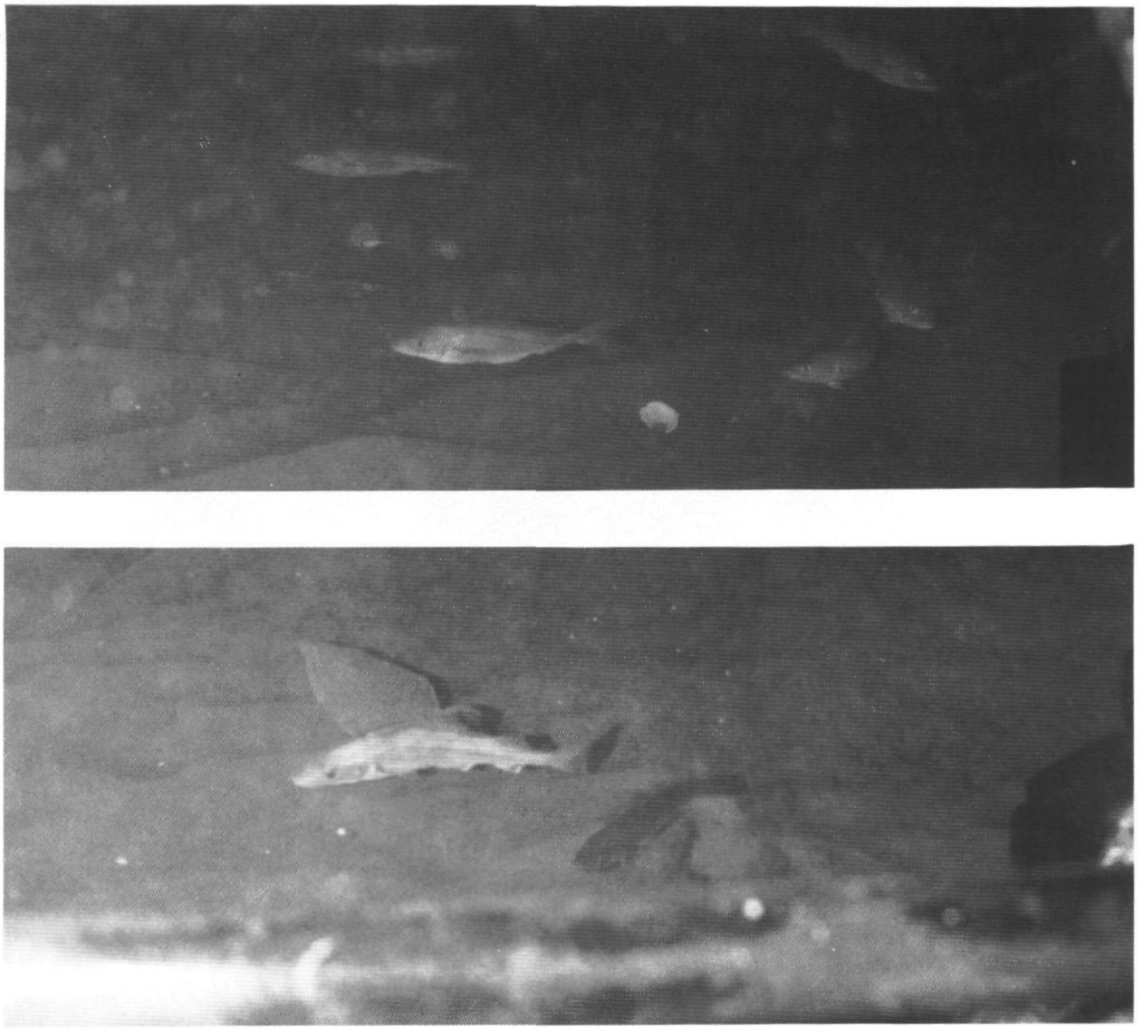
Again, when the ROV halogen lamp was switched on, fish were resting on or close to the bottom and in close proximity to the footgear. They appeared slow to react to the approaching footgear and did so in a haphazard direction with no ordered behaviour pattern. This behaviour was similar to that seen in regular night photographs.

Discussion

The results of the experiments led to the rejection of both null hypotheses and the acceptance of the alternate hypotheses. First, during regular night observations, fish did not show the ordered pattern of reaction behaviour as they did in daylight, so ambient light levels were considered to have been below the fish's vision threshold value of 10^{-6} lux, in agreement with Glass and Wardle's (1989) findings. Second, fish did not exhibit the ordered pattern of behaviour when ambient light levels were increased by the introduction of artificial light.

At night, with and without artificial light, variability in orientation of individual fish to the direction of the tow was greater than that by day. Fish were orientated randomly and appeared to be less active, with many resting on the bottom or in close proximity to the footgear, and some collisions were evident. During daylight video observations, only skate collided with the footgear. Skate showed no consistent orientation to the direction of tow, were often seen resting on the bottom, and swam in various directions as the footgear approached, similar to Beamish's (1966, 1969) observations. During night video recordings, with the ROV's halogen lamp on, several skate and flatfish were seen colliding with the footgear owing to slow reaction or to reaction in the wrong direction.

Several night and artificial light photographs showed various roundfish species apparently dashing away, centimetres away from the footgear, showing the typical U and S body shapes associated with fast starts (Webb, 1976). These startle reactions would generally be followed by cruising behaviour in roundfish or, in the case of flatfish, by settling to the bottom. This may account for the cruising behaviour observed, although less was seen than by day. The increase in startle behaviour from daylight to night and artificial light fishing hauls may be the result either of collisions or of "last-second" response to detection of the footgear. These day and night photographic observations of various roundfish behaviours are similar to the behaviour described for haddock



Figures 2 and 3. Flash photographs taken in the mouth of the trawl during night observations. The ordered distribution pattern is absent and fish are orientated randomly to the forward direction of the approaching gear.

by Glass and Wardle (1989). Flatfish, on the other hand, showed little difference in their light and dark behaviour, and showed no orientation and movement along the direction of the tow, in agreement with Beamish's (1969) observations.

To interpret the absence of the ordered pattern of behaviour during the night observations, it is necessary to look at the role of the distant-receptor activity of the fish's senses in the fish capture process. In the study of schooling formation and maintenance in fish, it is generally agreed that vision plays the dominant role, and that in the absence of vision, schooling and other visually controlled behaviour ceases (Glass *et al.*, 1986; Blaxter and Batty, 1987). Noise from the trawl doors and bobbins is thought to be clearly audible in the water far ahead of the trawl, possibly leading to a state of increased awareness of the fish which may occur before visual contact is established (Vyskrebentsev, 1971). The type of reaction manifested would be a function of illuminance and the type of school present, i.e. bottom-dwelling non-schooling species such as flatfish and skate; fish scattered in small schools; and dense aggregations or shoals.

As the trawl comes closer, fish probably rely on their distant-receptor senses (such as hearing, pressure gradient detection, and vision) to assess the situation, make a definitive analysis and react to the stimulus. Vyskrebentsev (1971) concluded that there was a definite link between distance at which danger was detected and reaction to it, on the one hand, and schooling on the other. As light intensity decreases beyond a fish's visual threshold, perception of sound and directional pressure gradients from the trawl components are assumed still to be perceived. Glass and Wardle (1989) concluded that

Figure 4. Flash photograph showing collision of cod with footgear during night observations. Fish are orientated perpendicular to the gear. No reaction is apparent.

these stimuli alone are not sufficient to produce an ordered pattern of behaviour, and our findings support this conclusion.

Nevertheless, artificial light on the footgear of the trawl, at night, was not sufficient stimulation for the fish to return to the ordered pattern of behaviour. Also, the use of the single ROV light, which was periodically turned on when adjusting the position of the vehicle, did

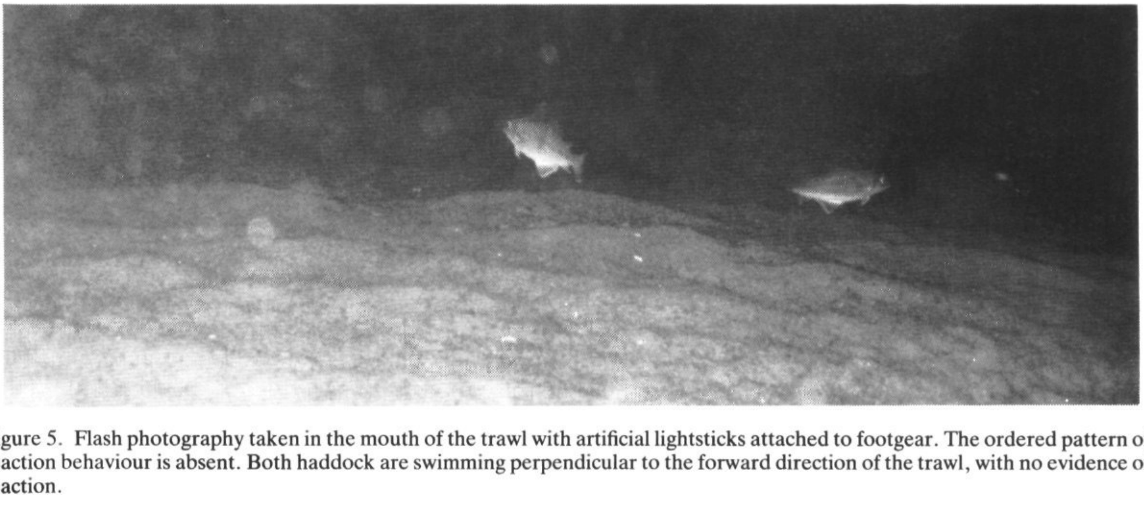


Figure 5. Flash photography taken in the mouth of the trawl with artificial lightsticks attached to footgear. The ordered pattern of reaction behaviour is absent. Both haddock are swimming perpendicular to the forward direction of the trawl, with no evidence of reaction.

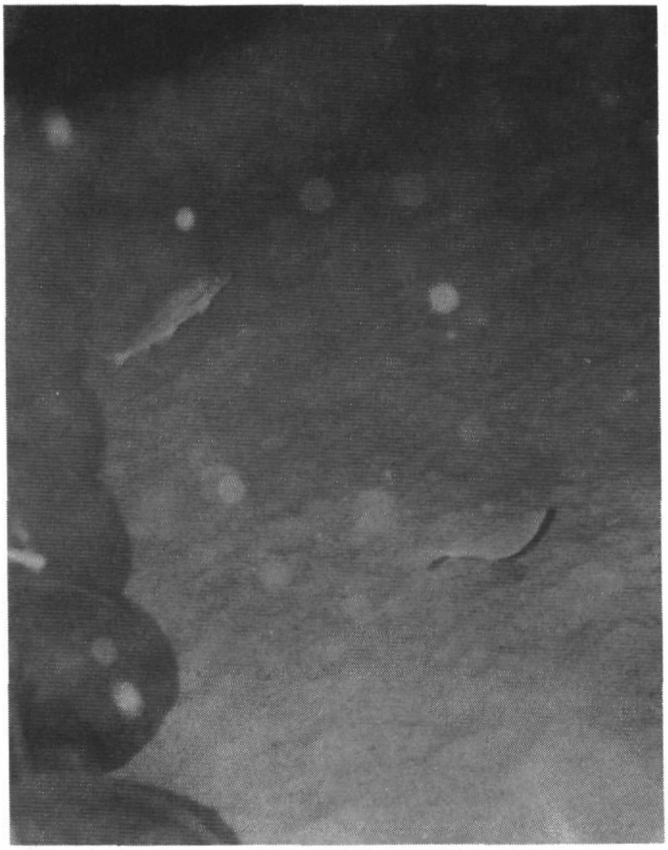


Figure 6. Flash photograph taken in the mouth of the trawl with artificial lightsticks attached to footgear showing near collision or seconds after collision with the approaching gear.

not cause the ordered pattern to resume as Glass and Wardle (1989) reported.

One hypothesis to explain the absence of an ordered pattern of behaviour with use of the artificial light was that the lights may have blinded the fish, whose eyes are dark-adapted, and caused immobility. Protasov (1970) found that the reverse process of dark-to-light adaptation in a fish's eye was much faster than light-to-dark adaptation, some aspects of it being completed in 30 s. Such rapid adaptation from a dark to a light cycle could explain why Glass and Wardle (1989) found an immediate resumption of the ordered pattern of behaviour in haddock when they switched on their ROV's powerful halogen lamps without startling the fish or blinding them. The lightsticks provide a string of diffuse, omnidirectional light source because there is no reflector controlling the light projection, as in the ROV's halogen lamp. This light string, the illuminance of which decreases over time, may have been sufficient for visual detection only as fish neared the footgear. Fish further ahead in the trawl path may not have been stimulated early enough to react in the ordered way when the net reached them: that would explain the higher variability of orientation and swimming behaviour of fish photographed during the artificial light haul than in regular night observations.

Although Glass and Wardle (1989) found a resumption of the ordered pattern in haddock when their ROV's 2 × 300 W halogen lamps were activated, activation of our ROV's single 250 W halogen lamp had no such effect. The ROV in each study was set up to look across and slightly back at the net to illuminate the trawl mouth. Our lamp has a 100 degree × 100 degree beam pattern (manufacturer's specifications). It is expected that Glass and Wardle's (1989) two lamps would have produced a broader beam pattern across the trawl's path. This might provide better contrast of objects for the fish, leading to possible earlier detection of the trawl and sufficient response time for fish to react in the ordered way. This improvement in beam patterns caused by more powerful light may also explain why Blaxter *et al.* (1964) could not stimulate the herding of herring at night when they used underwater lights (up to 100 W) mounted on the headline of their bottom trawl.

A second hypothesis for consideration when explaining the lack of an ordered pattern of behaviour at night, with and without artificial light, is that there might be a diel rhythmicity in awareness levels. Blaxter and Batty

(1987) have suggested that dark cycles or dark adaptations may result in a lower sensory awareness, a form of "sleep", or a heightened awareness, such as an increase in hearing ability, to compensate for loss of visual abilities, as part of the endogenous diel rhythms of fish. They suggested that this reduced level of awareness might occur because of the absence of predator threats and shoaling, both visually dependent behaviours, and the suspected need for energy conservation by fish. Introduction of diffuse light, such as by our lightsticks, or the presence of bioluminescent light may not be sufficient to break a dark cycle adaptation if one exists. This could explain why, at night (with and without the artificial lights), several roundfish were seen resting on the bottom both in the still photographs and in video observations and, in the latter case, seemed slow to react to the approaching footgear. Similarly, Barham (1970) reportedly observed that some species of mesopelagic myctophids, at night, were immobile, vertically orientated and failed to react to the artificial lights of the viewing submersible, suggesting a form of sleep. The hypothesis of diel rhythmicity in awareness may also explain the lack of a herding response in Blaxter *et al.*'s (1964) herring experiment with lights mounted on the trawl headline.

The aim of this study was to look at changes in behaviour of demersal fish near bottom trawls as light conditions changed. Difficulty in trying to artificially light a trawl to determine whether fish would react in a similar manner during both day and night has shown that the loss of ordered reactions in fish, at low light levels, may be more complex than originally thought. Although at night there is evidently a lack of orientation of fish to the stimulus of the net and a lower activity level, it is not yet clear whether this is a response to low light intensities, endogenous diel rhythms, or a combination of both.

More observational and experimental work is required to investigate the effects of appropriate artificial lights, bioluminescence, and raised background illumination on the reactions of fish to trawls. There is a strong need to study these in the context of diel rhythms and dark adaptative cycles inducing periods of lower awareness. Of major interest would be the testing of these hypotheses on midwater trawling of pelagic schools during both day and night.

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The reaction behaviour of walleye pollock (*Theragra chalcogramma*) in a deep/low-temperature trawl fishing ground

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In the trawling grounds of northern Japan and off the Kuril Islands, walleye pollock (*Theragra chalcogramma*) are fished at depths of 150 to 300 m. These fishing grounds have conditions of poor visibility and low temperature (0.5–2°C). Underwater observation by video camera showed a very weak response of fish and a general inactivity in the net. Most fish just seemed to be drifting passively toward the codend, although some turned to face the towing direction and swam along with the net for only a few seconds. Fish appeared hardly able to sustain a swimming speed that could match the towing speed of 3.5 to 4 knots. Concerning this inactive reaction of fish in the low-temperature fishing ground, the temperature effect on muscle contraction time was examined. The maximum swimming speed, calculated from muscle contraction time, for fish of 50 cm (total length) was 1.75 m s^{-1} at 0.5°C, but 2.5 m s^{-1} at 2°C, and 3.5 m s^{-1} at 10°C. This effect of temperature implies that the capture process of the trawl net when fished in deep/low-temperature grounds may differ from that in shallower grounds.

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Introduction

Underwater observation in the deep sea trawling grounds of northern Japan and off the Kuril Islands has shown passive drifting of targeted species without any characteristic reaction as the gear surrounds them. This passivity might be attributed to environmental factors such as light intensity (Glass and Wardle, 1989; Zhang and Arimoto, 1992) and water temperature (Wardle, 1989).

In the present experiments, the reaction behaviour of walleye pollock (*Theragra chalcogramma*) was studied in underwater video recordings made during trawl capture. To understand the swimming activity of these fish, experiments were also conducted to measure the muscle contraction time in relation to temperature.

Materials and methods

The trawl survey was conducted from July 1989 to October 1991, in fishing grounds at temperatures between 0.5 and 2°C, as summarized in Table 1. The water temperature at the towing depth was measured with an autorecording thermometer attached to the gear.

Fish behaviour was recorded for 30 min in each tow with a timer-controlled underwater video camera and artificial light (Inoue *et al.*, 1991). This apparatus was attached to several parts of the trawl net: at the mouth, at the extension piece, and at the baitings.

Concerning the swimming ability of walleye pollock, muscle twitch contraction time was measured in relation to fish size and muscle temperature (Wardle, 1977, 1980) on board the trawler as well as in laboratory experiments at the Usujiri Fisheries Laboratory of Hokkaido University between December 1991 and January 1992, using fish of 34–54 cm in total length, taken from the poundnet and kept for three weeks in a tank at 5–7°C prior to the experiment. The temperature effect was observed with the dorsal muscle block taken from each fish and its temperature adjusted to a known value in the range 0.5–17°C. Each block was examined at two to three different temperatures. This laboratory measurement of muscle contraction time was complementary to a previous study of the scale effect on contraction time in pollock (Ari-

Table 1. Analysis of behaviour under two towing conditions.

	2°C ground	0.5°C ground
Fishing area	Off Hokkaido, northern Japan	Off Kuril Islands
Temperature	2.0°C	0.5°C
Depth	180 m	150 m
Trawler	No. 67 Eishou-maru (37 m LOA, 1 800 PS)	No. 107 Seitoku-maru (50 m LOA, 2 800 PS)
Towing speed	3.8 knots	3.5 knots
Headline length	48 m	55 m
Trawl length	57 m	68 m
Number of tows	7	5
Number of fish analysed	2166	6105
INACTIVE behaviour*	73.0%	84.8%
FORWARD behaviour*	6.0%	5.0%
RANDOM behaviour*	21.0%	10.2%

* Values are percentage of individuals displaying each behaviour at a given temperature.

moto *et al.*, 1991). In addition, the swimming performance of walleye pollock in a holding tank (5.5 × 2.5 × 1 m deep) was video-recorded to obtain the stride length per tail beat.

Results

The reaction behaviour of walleye pollock was classified into three patterns: INACTIVE, showing no reaction to the passing trawl gear; FORWARD swimming, showing swimming in the towing direction; and RANDOM swimming, showing swimming in a random direction. The proportions of these patterns in each fishing ground are summarized in Table 1. INACTIVE occupied the major portion, 73–85% of individuals, in which the fish were overtaken and passed towards the codend without showing any effort to swim forwards. Even for active individuals, FORWARD or RANDOM swimming was insufficient to maintain their position in relation to the towing speed. Active swimming was observed to continue for only a few seconds, so that the fish were consequently engulfed and passed towards the codend.

When patterns were compared between the two fishing grounds, a higher proportion of INACTIVE and a lower proportion of RANDOM was observed on the 0.5°C ground. This difference in swimming activity could be attributed to the water temperature at the towing depth in each fishing ground.

Figure 1 shows the effect on muscle contraction time of acclimatization temperatures of 0.5–17°C. It can be seen that the muscle contraction time extends from 40–60 ms at a muscle temperature of 10°C to 90–100 ms at 0.5°C. The muscle contraction time limits the maximum swimming speed of fish (Wardle, 1975). For this purpose, the maximum tail beat frequency (F) can be calculated from the muscle contraction time (T_m) as $F = (2T_m)^{-1}$. Thus the maximum swimming speed of a fish can be expressed as $U_{max} = kLF$, where L is the body length and k the stride length. The k value was determined as a maximum of 0.7 in a rather slow movement in the holding tank.

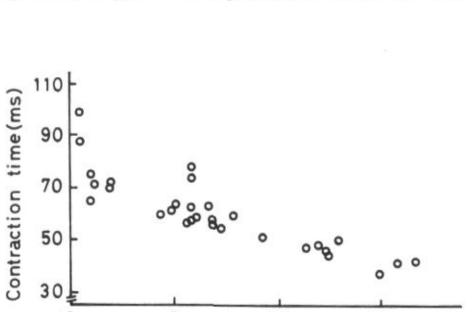

Figure 1. Muscle contraction time of walleye pollock (*Theragra chalcogramma*) of 34–54 cm total length, measured at different temperatures.

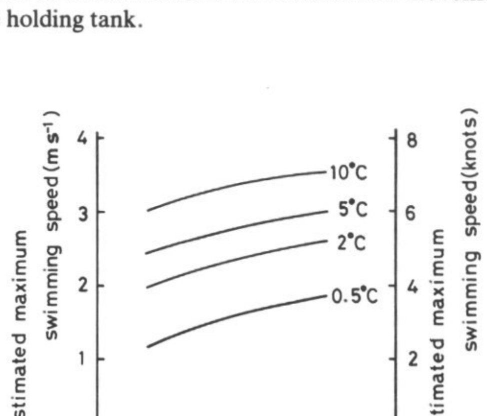

Figure 2. Relationship between estimated maximum swimming speed of walleye pollock (*Theragra chalcogramma*) and fish size, at various temperatures.

Based on the above theory, the maximum swimming speed of walleye pollock was estimated (Fig. 2) in relation to fish length and temperature. For pollock of 20 cm (total length) at 0.5°C, U_{max} is 1.0 m s^{-1}, whereas for fish of 50 cm, U_{max} is predicted to be 1.75 m s^{-1}; both these values are lower than the towing speed of 1.8–2 m s^{-1} operated on the fishing ground. Results for the effect of temperature on muscle contraction time indicate better swimming performance of fish at higher temperatures.

Discussion

Analysis of video recordings of the swimming behaviour of walleye pollock in the mouth area and inside the towed net revealed that 70–80% of individuals drifted inactively toward the codend. The remaining 20–30% swam actively, but seemed hardly able to sustain a swimming speed that could match the speed of the towed net for even a few seconds. Stable and steady swimming was not observed in any of the video recordings. Concerning the influence of artificial light, it was often observed that the fish changed their swimming pattern, seemingly owing to lighting conditions. To prevent misinterpretation of behaviour, analysis was restricted to the behaviour pattern observed when the fish first came into the camera view. Besides, it is noteworthy that the presence of the light did not seem to disrupt the inactive drifting behaviour.

The effect of temperature on muscle contraction could explain the inactive behaviour on the 0.5–2°C fishing grounds. The maximum swimming speed of a fish of 50 cm total length is estimated to be 1.75 m s^{-1} at 0.5°C, and 3.5 m s^{-1} at 10°C (Fig. 2). The fish can maintain this burst speed for only a few seconds. This tendency for walleye pollock is similar to recent results obtained for cod (*Gadus morhua*) (Videler and Wardle, 1991). A maximum swimming speed lower than the towing speed in the low-temperature fishing ground implies little chance of escape by the fish from the fishing gear. This difference in swimming activity owing to temperature suggests that the capture process of the trawl net may differ from that in the warmer shallower grounds.

Acknowledgements

We are grateful to the National Federation of Medium Trawlers for conducting the on-board experiment during the cruise of Japan–USSR Joint Research Project. Thanks are also due to the captains and crew of No. 107 Seitoku-Maru and No. 67 Eishou-Maru for their help during the cruise.

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Selectivity in shrimp trawl codends tested in a fishery in Greenland

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A selectivity study using a standard commercial shrimp trawl with trouser codends was carried out on two cruises in Greenland waters. On one cruise, codend mesh sizes of 45 and 60 mm were tested with a control codend of 15 mm, and on the other cruise the same mesh sizes were tested in two localities but with a control codend of 28 mm. From these experiments, selectivity curves have been described by a logit function the parameters of which have been estimated using an iterative likelihood method. Comparative fishing experiments with codend mesh sizes of 45 and 60 mm showed a significant reduction in catch in the 60 mm mesh codends of small shrimp (below 22 mm carapace length) in the order of 40–50%. A reduction of large shrimp (above 22 mm carapace length) in the order of 15–30% was also seen, however. In addition, a comparative fishing exercise with 45 mm diamond mesh and 45 mm square mesh codends showed no significant difference in the length composition of the catch for the two codends.

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Introduction

The North Atlantic fishery for deepwater shrimp (*Pandalus borealis*) is of great economic importance to Greenland. Fishing effort for shrimp has been increased in recent years, and has given rise to concern about the exploitation pattern of these shrimp stocks, because significant quantities of small shrimp are discarded and the long-term yield of the Greenland shrimp stock would increase if catching these small shrimp could be avoided.

This paper establishes selectivity curves for shrimp in a Greenland commercial trawl with diamond-mesh codends, using data derived from research surveys carried out in the Davis Strait in 1991. The consequences of increasing codend mesh size from 45 mm to 60 mm in the commercial shrimp fishery are evaluated. Furthermore, a comparison is made between 45-mm diamond-mesh and 45-mm square-mesh codends.

Material and methods

Survey 1

Survey 1 was carried out from 1 July to 14 July 1991 in NAFO Divisions 1B and 1C in West Greenland. Fishing locations were changed during the survey as no small shrimp occurred after some time in a specific location. The trawler used was MT "Pamiut", a 722 GRT 2000 hp stern trawler. The doors used were of the type "Perfect Greenland", size 370*250 cm, weight 2420 kg. The trawl used was an "Arctic Skjervoy" with a mouth circumference equivalent to 3000 meshes in 20 mm half mesh. A bobbin footrope and twin "trouser" codends were used (in line with normal commercial practice). This trawl is commonly used in the Greenland commercial offshore shrimp fishery.

A small mesh vertical panel (mesh size 20 mm beginning 10 m behind the footrope) was mounted along the centreline of the trawl to improve the equalization of the numbers of fish entering the two codends. Each mesh size/mesh shape combination (15 mm diamond to 45 mm diamond, 15 mm diamond to 60 mm diamond, 45 mm diamond to 60 mm diamond, and 45 mm diamond to 45 mm square) was tested, with codends being interchanged between starboard and port sides when half of the hauls were completed.

Fishing was carried out 24 h a day and the haul duration was variable. Trawling speed was about 2.5 knots. The c.p.u.e. was between 230 kg h^{-1} and 675 kg h^{-1} per codend for the different experiments (Table 1).

Table 1. Summary of catch statistics for shrimp by reference codend (ref.) and test codend for survey 1 and survey 2. 45 mm<> and 45 mm# are respectively abbreviations for a codend with 45 mm diamond mesh size and 45 mm square mesh size. C.p.u.e. denotes catch per hour per codend, and effort is haul duration in decimal hours. SB test nos are numbers of hauls with the test codend on the starboard side of the trawl, and MIN and MAX are minimum and maximum.

Survey 1				
Codend ref.	15 mm<>	15 mm<>	45 mm<>	45 mm<>
Codend test	45 mm<>	60 mm<>	60 mm<>	45 mm#
Nos. of haul	9	5	8	6
SB test nos.	5	4	4	3
Total effort	8.4	10.6	9.2	13.7
Mean effort	0.9	2.1	1.1	2.3
MIN depth m	234	332	324	327
MAX depth m	385	379	440	482
Total catch ref.	4600	3736	6178	3132
C.p.u.e. ref.	547	351	675	229
Total catch test	3392	2589	4441	3372
C.p.u.e. test.	403	243	485	246
Survey 2 transect 2				
Codend ref.	28 mm<>	28 mm<>	45 mm<>	
Codend test	45 mm<>	60 mm<>	60 mm<>	
Nos. of haul	6	6	6	
SB test nos.	0	6	6	
Total effort	6	6	6	
Mean effort	1	1	1	
MIN depth m	340	340	336	
MAX depth m	369	360	360	
Total catch ref.	1844	2333	3365	
C.p.u.e. ref.	307	389	561	
Total catch test	1591	1360	2376	
C.p.u.e. test	265	227	396	
Survey 2 transect 3				
Codend ref.	28 mm<>	28 mm<>	45 mm<>	
Codend test	45 mm<>	60 mm<>	60 mm<>	
Nos. of haul	6	6	6	
SB test nos.	0	6	6	
Total effort	6	6	6	
Mean effort	1	1	1	
MIN depth m	222	219	246	
MAX depth m	277	277	276	
Total catch ref.	1465	1169	2420	
C.p.u.e. ref.	244	195	403	
Total catch test	2515	1214	1174	
C.p.u.e. test	419	202	196	

Survey 2

Survey 2 was carried out from 18 to 30 July 1991 on the slope off "Store Hellefisk Bank" in NAFO Division 1B in West Greenland on board the 2480 GRT commercial trawler "Tasiilaq". The doors and gear used were the same as for survey 1.

The experiments were carried out as a trouser trawl experiment along two transects at a depth of approximately 200–300 m and 300–400 m. No vertical separator panel was used in this survey. At each transect, six hauls were carried out with each combination of the three different codend mesh sizes: 28, 45, and 60 mm stretched. This gave a total of 18 hauls at each transect. The c.p.u.e. was between 200 kg h^{-1} and 561 kg h^{-1} per codend for the different experiments (Table 1).

All fishing hauls were of a duration of one hour at a towing speed of 2–2.5 knots. Fishing was only carried out during daylight hours. Direction of trawling on each transect was the same during all hauls, and the position of each mesh size, either starboard or port, was also the same for each combination of codends tested.

A summary of results for the two surveys is given in Table 1.

Sampling

A representative sample (4–5 kg) of the shrimp catch of each codend was taken from different parts of the catch, and the carapace length was measured with a caliper to the nearest 0.1 mm and grouped into 0.5 mm intervals.

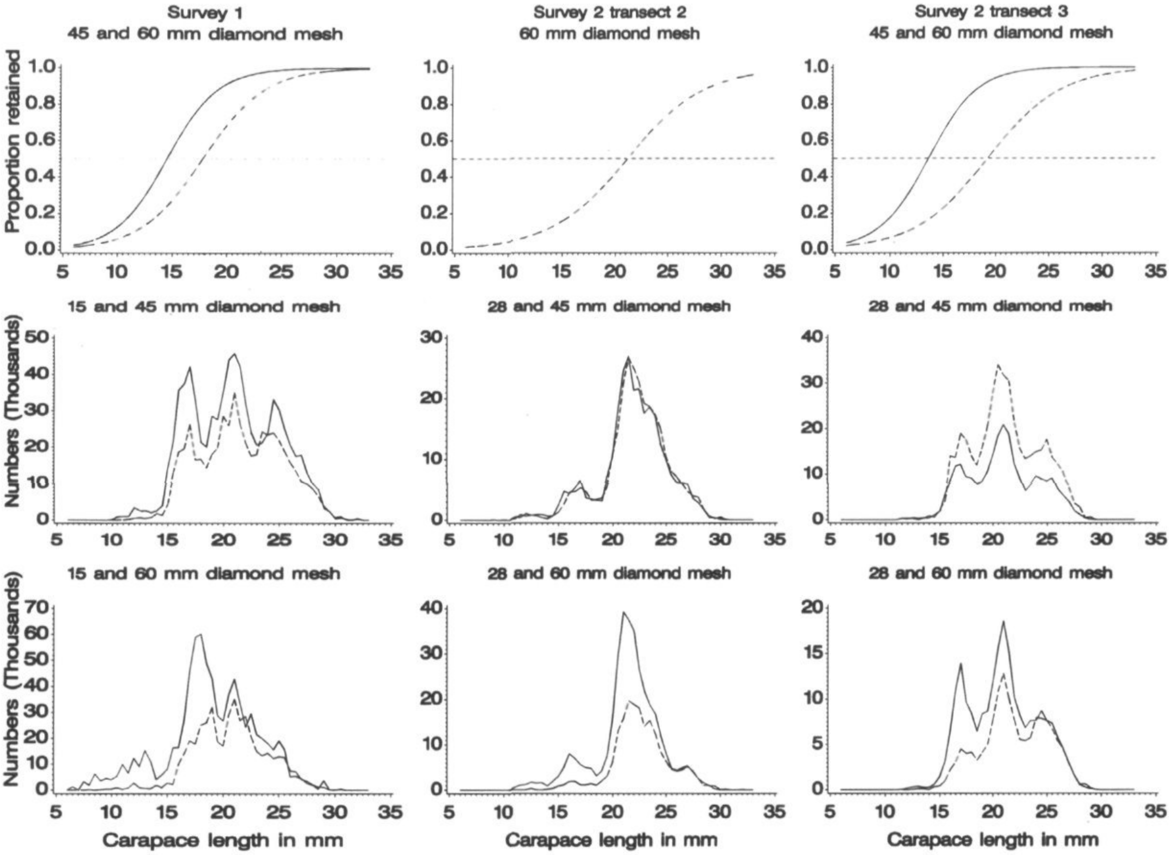

Figure 1. Selection ogives and length-frequency curves for shrimp. Each column shows corresponding values for a survey or transect. Top row, selection ogives (solid curves, 45 mm mesh size; broken curves, 60 mm mesh size). Middle row, length frequency curves for test codend (mesh size 45 mm, broken curves) and reference codends (mesh sizes 15 and 28 mm, solid curves). Bottom row, length frequency curves for test codend (mesh size 60 mm, broken curves) and reference codends (mesh sizes 15 and 28 mm, solid curves). Note differing vertical scales in middle and bottom rows.

Calculation method

In this paper we use the Millar and Walsh (1992) model, as this model has been developed to calculate the selection parameters from trouser codend selectivity experiments.

The selection parameters are calculated both with the assumption of equal efficiency of the two codends and with that of unequal efficiency.

$$\text{Ø}(L) = p * \exp(a+b*L)/[(1 - p) + \exp(a+b*L)]$$

where: Ø(L) is the probability of a length L shrimp being caught in the large mesh, given that it is caught; p is the probability that a fish entering the gear will go into the large mesh codend; a and b are selection parameters; L50 is 50% retention length (L50 = −a/b); S.R. is Selection Range [S.R. = 2*ln(3)/b]; and S.F. is Selection Factor (S.F. = L50/mesh size).

In survey 1, catches from hauls with the same mesh size combination have been pooled for estimations of the selection parameters. In survey 2, data have also been pooled according to mesh size combination, but selection parameters are estimated for each transect separately, as size distributions differed between the two transects.

Results

Survey 1

Figure 1 shows the selectivity curves for shrimp for 45 and 60 mm mesh size codends compared with the 15 mm mesh size codend. For 45 mm it was impossible to calculate parameters with p = 0.5. Only when p was estimated (p = 0.44) could selection parameters then be estimated, giving an L50 of 14.5 mm carapace length (Table 2). The estimates are based on rather low numbers of shrimp less than L50 (Fig. 1) and therefore may be regarded as of doubtful accuracy. For 60 mm the estimate of p was approximately 0.5 and there is therefore little difference between the selection parameters

Table 2. Survey 1: selectivity parameters for each mesh size combination. Selectivity parameters were fitted with and without the assumption of equal efficiency of the two codends. Values in parentheses are standard errors.

	15/45 mm	15/60 mm	
	p	p = 0.5	p
a	−6.24	−6.19	−6.28
	(0.10)	(0.03)	(0.04)
b	0.4298	0.3443	0.3533
	(0.007)	(0.002)	(0.008)
p	0.44		0.49
	(0.001)		(0.004)
L50	14.53	17.99	17.80
	(0.03)	(0.01)	(0.04)
S.F.	0.32	0.30	0.30
S.R.	5.11	6.38	6.22

calculated by the two options (Table 2). In the size distribution curve the L50 of 17.8 mm is seen to be placed in the part of the curve with the highest frequency of shrimp, and the estimated parameters should therefore be of good accuracy.

Survey 2

Table 3 shows the selectivity parameters for shrimp calculated for 60 mm codend mesh size in transect 2 and for 45 and 60 mm codend mesh size in transect 3. Parameters are calculated when assuming both equal fishing efficiency of the two codends (estimation of a and b) and unequal efficiency (estimation of a, b, and p). For the 45 mm mesh size, selectivity parameters could only be estimated at transect 3 with unequal efficiency.

In all cases p was estimated to be above 0.5, and only in the case with the 45 and 60 mm mesh sizes in the codends to differ significantly from 0.5. This means that the larger mesh size has a small tendency to be more effective in catching shrimp than the control mesh size. As a consequence L50 is higher and the selection range is wider when p is estimated than when p is assumed to be 0.5.

From the catch distribution by length group in the two transects (Fig. 1), it is obvious that the selection curves derived from the 45 mm mesh size are difficult to establish or may be uncertain owing to the few data defining the left side of the curve. Selection curves for the 45-mm mesh size are shown in Figure 1 for transect 3.

In the 60 mm experiments, the L50 values range between 18.6 and 21.2 mm, with the highest values in transect 2 (Table 3). Selection curves and length distributions of the catches are shown in Figure 1. Selection ranges were found to be between 6.8 and 8.0 mm. The selection factors were found to be in the order of 0.30 to 0.35.

Comparison between 45 mm and 60 mm diamond mesh size codends

The results of fishing experiments comparing the commercial 45 mm diamond mesh size codends against the 60 mm diamond mesh size are given in Table 4. The catches have been pooled by carapace length group below and above 22 mm, approximately corresponding to a count of 120 shrimp per kg. This division splits the catch up into the small shrimp, which are often discarded as of low market value, and the large shrimp of high market value (Lehmann and Degel, 1991). It is assumed that the two codends have the same catch efficiency.

Comparison between 45 mm diamond and 45 mm square mesh codends

Table 4 and Figure 2 show the results of the experiments with 45 mm diamond and 45 mm square mesh codends. In total the catch by square mesh was little higher than that with diamond mesh. In half of the hauls the diamond mesh codend had more catch than the square

Table 3. Survey 2: selectivity parameters for each transect and each of the mesh size combinations. Selectivity parameters were fitted with and without the assumption of equal efficiency of the two codends. Values in parentheses are standard errors.

	Transect 2		Transect 3		
	28/60 mm		28/45 mm	28/60 mm	
	p = 0.5	p	p	p = 0.5	p
a	−5.87	−5.82	−5.85	−6.03	−5.54
	(0.05)	(0.07)	(0.22)	(0.08)	(0.11)
b	0.2798	0.2747	0.4302	0.3241	0.2879
	(0.002)	(0.004)	(0.014)	(0.004)	(0.007)
p		0.51	0.65		0.52
		(0.004)	(0.001)		(0.004)
L50	20.98	21.18	13.59	18.59	19.24
	(0.02)	(0.13)	(0.08)	(0.03)	(0.13)
S.F.	0.35	0.35	0.30	0.31	0.32
S.R.	7.85	8.00	5.11	6.78	7.63

Table 4. Comparison between catch weight of shrimp from commercial 45 mm diamond mesh codend and 60 mm diamond mesh codend for surveys 1 and 2, and for 45 mm diamond mesh codend and 45 mm square mesh codend for survey 1. Catches are split into shrimp below and above 22 mm carapace length (see text). Numbers per length group are converted to "calculated catch" weight by a condition factor of 0.00059594 (Lehmann and Degel, 1991). Numbers in parentheses are percentages.

Codend mesh size mm	Hauls Nos	Catch kg	Catch below 22 mm kg	Catch above 22 mm kg
Survey 1				
45 mm diamond	8	5883(100)	3069(100)	2814(100)
60 mm diamond	8	4292 (73)	1873 (61)	2419 (86)
Catch reduction		1591 (27)	1196 (39)	395 (14)
45 mm diamond	6	2969(100)	911(100)	2058(100)
45 mm square	6	3233(109)	959(105)	2274(110)
Catch gain		264 (9)	48 (5)	216 (10)
Survey 2				
45 mm diamond	12	5912(100)	2183(100)	3729(100)
60 mm diamond	12	3653 (62)	1069 (49)	2584 (69)
Catch reduction		2259 (38)	1114 (51)	1145 (31)

mesh codend, and vice versa. Also the length frequency curves for the two meshes were very alike.

Discussion

Several experts have doubted whether an increase in mesh size produces the anticipated effect upon size selection in shrimp trawls as reviewed by Vendeville (1986). Valdemarsen (1989) advanced a hypothesis which could explain this, based upon the behaviour of the shrimp in the catch process in conventional trawls. When disturbed, shrimp react with one or more backward jumps in random directions, with their long antennae and pointed rostrum directed against the disturbance. This also happens when shrimp are caught by a trawl and hit a netting panel. If the mesh size is large enough and the mesh open, the shrimp can by chance jump either out through the netting or alternatively into the trawl. In a codend, shrimp to some degree aggregate into a filter which can retain the smaller individuals. This would mean that selection to some extent stops as the catch builds up in the codend, and that L50 should decrease, and selection range increase, with the catch size. Contrary to these considerations, a selection study in the Greenland commercial shrimp fishery showed that L50 was constant and selection range decreased significantly with increasing haul duration, which was directly correlated to catch size (Degel *et al.*, 1991).

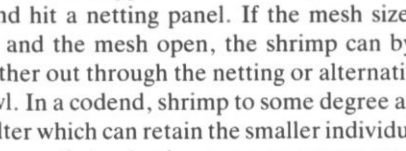

Figure 2. Length frequency curves for shrimp caught during survey 1 with 45 mm diamond mesh (solid curve) and 45 mm square mesh (broken curve).

Thomassen and Ulltang (1975) and Sakhno and Sadokin (1980) have established selection ogives based on a few hauls with low catch size. However, only a few selection studies of shrimp have been carried out based on catch sizes at a commercial scale.

In the present study it was possible to show that selection of shrimp did occur in a commercial-scale fishery with a shrimp trawl for both the 45 mm and the 60 mm diamond mesh codend, and that the L50 was different for mesh sizes. The calculated selection factors, which ranged between 0.30 and 0.35, are somewhat lower than those obtained by Thomassen and Ulltang (1975) and Sakhno and Sadokin (1980), which were about 0.45, but are at the same level as the selection factors estimated by Valdemarsen and Mikalsen (1991) and Degel *et al.* (1991) of about 0.36.

The result that equal size distributions of shrimp were obtained using the 45 mm diamond mesh and square mesh contrasts with that obtained by Thorsteinsson (1992), where the use of square mesh codends in the Icelandic fjord shrimp fishery reduced catches of small shrimp. The difference could be due to the smaller trawl used in Iceland and the much smaller size of shrimp fished in the Icelandic fjord fishery, compared with the Greenland offshore fishery.

The reduction in the catch of small shrimp (below 22 mm carapace length) in the 60 mm codend, compared with the commercially used codend of 45 mm, was between 39 and 51%, and reduction of shrimp larger than 22 mm carapace length was between 14 and 31%. This result is due to the rather "flat" selection ogive with a selection range (S.R.) between 6 and 8 mm carapace length. Adoption of the 60 mm codend would result in a considerable loss of high-value shrimp (intolerable for the economy in the shrimp trawl fishery) and calls for the development of methods to release small shrimp from the trawl other than simply increasing mesh size.

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Escape of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) from Danish seine codends during fishing and surface hauling operations

Bjørnar Isaksen and Svein Løkkeborg

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The escape of cod (*Gadus morhua* L.) and haddock (*Melanogrammus aeglefinus* L.) from Danish seine net codends during the surface hauling operation was studied. Fish that escaped during bottom hauling and surface hauling were separated by using a two-part cover consisting of a main cover with an aft detachable cover piece. As soon as the covered codend appeared at the surface, the detachable cover was detached from the main cover and handed over to another boat. The main cover was closed before surface hauling started. About half the total number of fish escapes took place during surface hauling. Fish that escaped on the surface were significantly larger than fish that escaped during bottom hauling. Selection ogives for the bottom and surface hauling, as well as the overall selection ogives for polyamide and polyethylene codends, are shown.

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Introduction

In the early 1980s the minimum mesh size in Danish seine net and trawls was increased in Norwegian areas north of 64° latitude. The mesh size in polyamide codends was increased to 135 mm for both gears, but the increase was larger for Danish seine than for trawls, at 25 and 10 mm, respectively. This increase led to reductions in catch rates, and fishermen using Danish seine net claimed that the catch reduction was most pronounced for their catches because many fish, especially haddock just above the minimum landing size (39–45 cm), escaped during the surface hauling operation. The main objections from the Danish seine fishermen of having the same mesh size as trawls were thus based on differences in hauling operations at the surface. In addition, trawls have heavier material in the codend than Danish seines; double, plaited, and bonded 6–8 mm polyamide as against single, twisted 2–3 mm polyamide.

New selectivity experiments using the trouser-trawl method were conducted in 1986 to study the effects of the mesh size increase in Danish seine net and to establish selection factors for the 135 mm, polyamide codend (Isaksen and Larsen, 1988). The selection factors obtained were higher than those measured in the early 1980s using the covered codend method (Jakobsen, 1983). Partly owing to this result and partly owing to the fishermen's energetic approaches to the authorities, a temporary arrangement with a 10 mm smaller mesh size for Danish seine was established in 1988, an arrangement that is still in force.

However, before the authorities managed to cope with the situation, a few fishermen found their own solution to the problem of surface selection. Instead of the light codends normally used by this fleet, the fishermen provided themselves with heavy, stiff codends of double, plaited 7–8 mm polyethylene, normally used by large stern trawlers in Iceland and known as the "Icelandic codend". The minimum mesh size for polyethylene codends is 10 mm larger than for polyamide codends. The peculiarity of the polyethylene codend is the tendency of its meshes to close during surface hauling, especially for brand new codends.

The objectives of this study were to obtain a better understanding of the selectivity process and to examine the allegation of a considerable surface selection in Danish seine nets. A new method involving two codend covers (a "tandem" cover) was used to separate fish escaping during bottom hauling and surface hauling. The behaviour of fish escaping from the codend was observed with an underwater television camera. Both polyamide and polyethylene codends were studied.

Materials and methods

The experiments were conducted in June 1991 off the east coast of Finnmark in northern Norway at 50 m depth. Three vessels were engaged in the experiment with the "tandem" covered codend method; the chartered 67 ft Danish seiner MS "Heidi Anita", the 48 ft RV "Fjordfangst", and a 12-foot rubber boat. MS "Heidi Anita" was equipped with a 180# (300 mm) seine net with rope wings and lead droppers, and five coils of 28 mm rope (150 kg/coil) were used. Two codends were used during the two-day experimental period, a polyamide (PA) codend on the first day and a polyethylene (PE) codend on the second (Table 1). Three hauls were made each day.

Both covers used were of polyamide. The first and main cover (Fig. 1, point 2) had a length of 20 m and a stretched circumference of 23.3 m, equal to twice the width of the codends. This cover was made of twisted PA (210/60), with a mesh size of 60 mm. The main cover was attached to the seine net 1 m ahead of the PE codend, and 3 m ahead of the PA codend. In both cases the end of the main cover would be 5 m aft of the codend. The second, detachable, cover (Fig. 1, point 3) had a length of 6 m and a mesh size of 48 mm, and was made of a thinner, lighter material (PA 210/36).

Before shooting the gear, the releasable cover was attached to the main cover by simple chain-stitch ("monkey-braiding"). Normal fishing procedure was followed until the gear appeared at the surface. Instead of slowing up and starting to haul the gear through the power block, the seiner went forward at a speed of about two knots. The rubber boat went quickly up to the connection between the main and detachable cover, a rope was tied around the detachable cover just aft of the connection, a 60 cm buoy was attached to this cover, and the chain-stitch between the covers was opened. The rubber boat then went to the main cover to tie the codline before the seiner stopped and normal surface hauling began (Fig. 1). The time elapsed between release of the aft cover and closure of the main cover was less than 2 min, and very few fish were seen escaping meanwhile. The released cover was picked up by RV "Fjordfangst", while MS "Heidi Anita" took care of the catch in the main cover and codend.

Underwater observations of the codends without cover were made during the surface hauling operation. Before the codend reached the surface, RV "Fjordfangst" manoeuvred up to a position aft of MS "Heidi Anita", about where the codend would appear. As soon as the codend was visible, a small remote-operated vehicle ("Manta" equipped with a light-sensitive underwater (SIT) camera) was launched and directed towards the aft of the codend, where most of the observations were made.

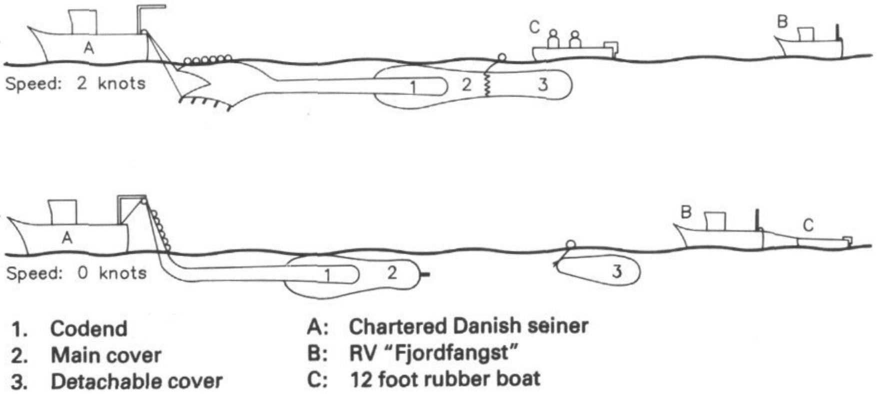

Figure 1. Design of the main and detachable covers ("tandem" cover), and the procedure for detaching the cover.

Table 1. Gear parameters for the polyamide and polyethylene codends.

Codend	Length[a] (m)	Width (meshes)	Mesh size (mm)	Dimensions
Polyamide	12	90	125.5	Double 4 mm plaited
Polyethylene	14	80	138[b]	Double 7 mm plaited

[a] 95#.

[b] Nominal 135 mm.

Table 2. Numbers of mean lengths (cm) of cod and haddock in the different hauls made by the "tandem" cover method.

		Cod						Haddock					
		Codend		Main cover		Detachable cover		Codend		Main cover		Detachable cover	
Haul no.	Codend material	No.	x̄	No.	x̄	No.	x̄	No.	x̄	No.	x̄	No.	x̄
1	PA	1 024	48.5	1 094	42.6	802	37.1	168	42.4	509	38.4	454	34.1
2	PA	2 369	54.1	857	42.2	836	36.1	156	43.2	275	35.8	582	33.5
3	PA	1 385	51.0	1 110	41.9	1 508	35.1	332	42.1	559	35.2	514	34.1
Total	PA	4 778	—	3 061	—	3 146	—	656	—	1 343	—	1 550	—
4	PE	351	46.1	156	37.5	348	32.3	299	39.3	217	32.5	368	30.4
5	PE	691	50.8	648	40.7	1 163	36.2	312	44.6	1 541	33.6	885	32.7
6	PE	537	52.2	649	42.1	1 509	37.6	460	39.6	2 570	33.5	3 043	32.5
Total	PE	1 279	—	1 453	—	3 020	—	1 071	—	4 328	—	4 296	—

Results

Underwater observations

Sunshine and high light levels at the surface made detailed observations with the SIT camera difficult. Analyses of the videotaped observations, however, revealed differences in the escape behaviour of cod and haddock. Haddock were often seen chasing around in the codend. The fish might, for example, suddenly swim right onto the net panel and make a few vigorous rushes. Small fish escaped in one operation, whereas fish of medium size often went halfway through the net at their first attempt. These fish escaped successfully after a few seconds' rest and a new attempt. Large haddock (>50 cm) were often gilled in the PA codend, but not in the PE codend.

Cod displayed calmer swimming behaviour, and fewer cod were seen escaping. Escaping fish first made a short (few seconds) "inspection" of the escape possibilities, and then swam calmly through the panel, mostly in one operation. Very few cod were gilled in the PA and PE codends.

Selectivity experiments

The numbers of cod and haddock caught in the codends and the two covers are given in Table 2. Except for cod in the PE codend, about half the total escapes occurred during surface hauling. The length-frequency distributions of cod and haddock in the codends and the two covers are shown in Figure 2a–d. Except for haddock in the PE codend, there were distinct differences in the length distributions of fish escaping during the bottom and the surface hauling period, with larger fish escaping at the surface. The mean lengths were significantly different for all combinations of codends and covers (Table 2; Mann-Whitney U-test, $p < 0.0001$).

Figure 3a–d shows the proportion of the total escapes that occurred during bottom and surface hauling, respectively, for each length group. For cod in the PA codend (Fig. 3a), most fish smaller than 36 cm escaped during bottom hauling, whereas cod larger than 42 cm mostly escaped during surface hauling. A similar trend, although not so clear, is seen also for the other combinations of fish and codend. The lengths of fish that managed to escape in equal numbers during the two phases of hauling are 39 cm for cod and 37 cm for haddock in the PA codend, and 44.5 and 35 cm, respectively, for the PE codend.

The overall selection curves for cod and haddock in the two codends are shown in Figure 4a–d. The PA and PE codends gave similar selection factors for cod, 3.8 and 3.7 respectively, whereas the selection factors differed more for haddock, 3.7 and 3.4 respectively. The selection ranges for the PA and PE codends were quite similar, both for cod, 10.7 and 9.8 cm, and for haddock, 8.6 and 9.8 cm, respectively.

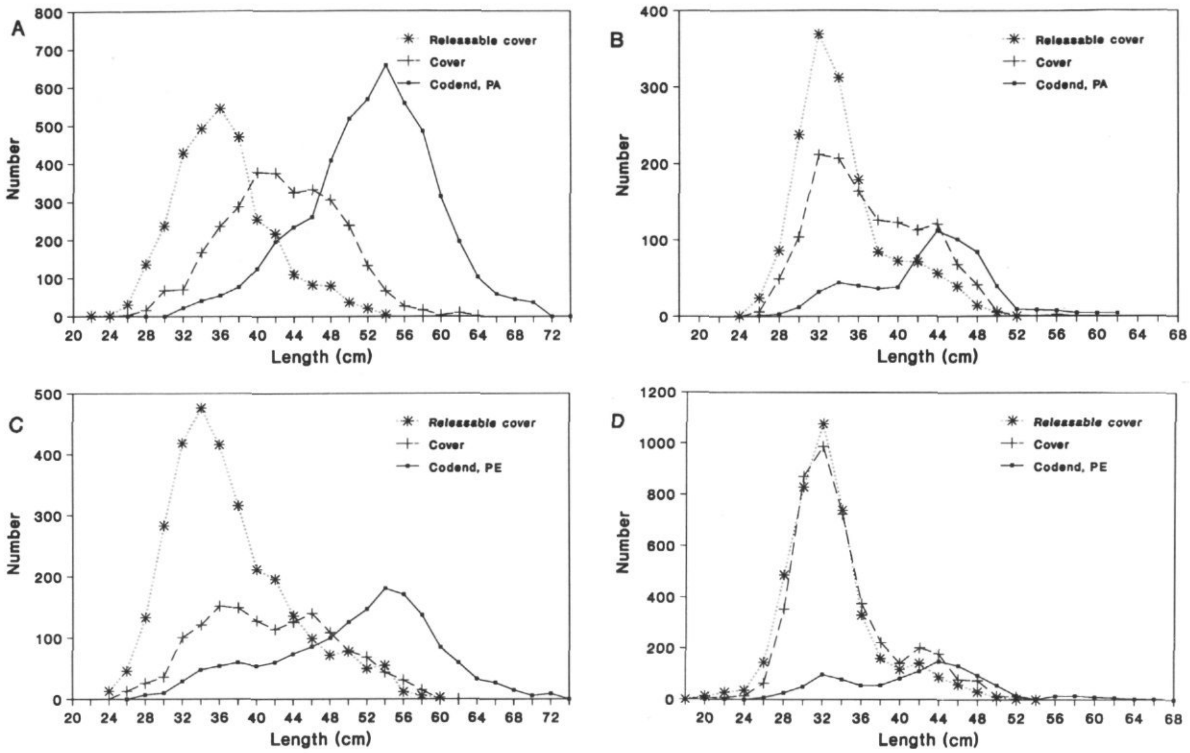

Figure 2. Length-frequency distributions of cod (a and c) and haddock (b and d) caught in the PA codend (a and b), the PE codend (c and d), the main cover (surface selection) and the detachable cover (bottom selection), using the "tandem" cover method.

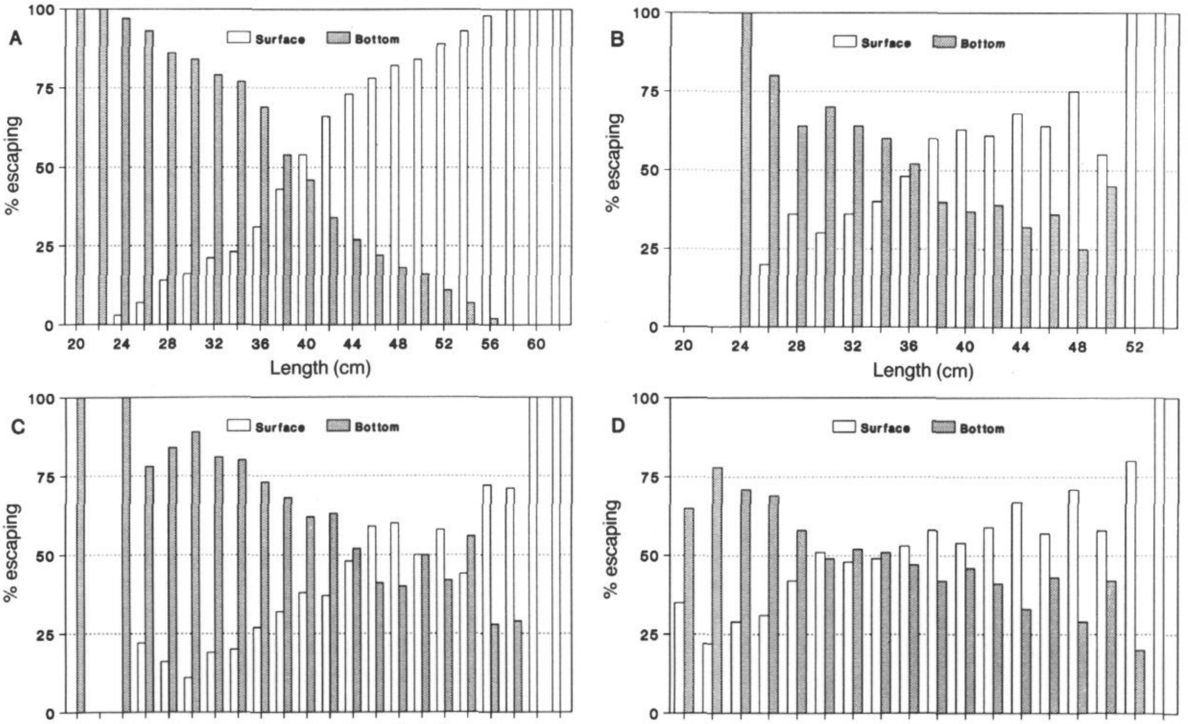

Figure 3. The proportions of cod (a and c) and haddock (b and d) escaping at the bottom and at the surface using the PA codend (a and b) and the PE codend (c and d).

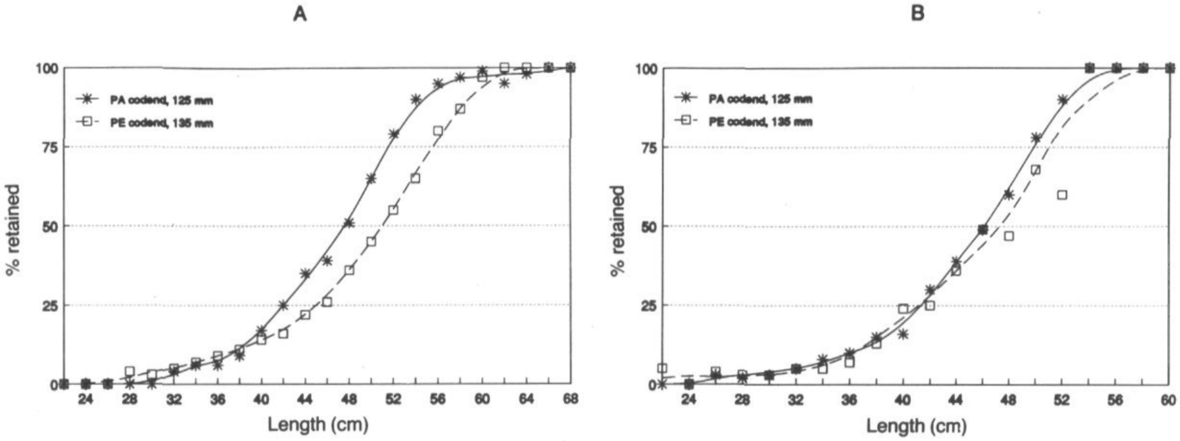

Figure 4. Selection curves for cod (a) and haddock (b) in the PA and the PE codend. The low point for 52 cm haddock is based on a small number of fish.

Discussion

The underwater television observations, although not quantitative, confirmed the fishermen's allegations of surface selection, and showed that haddock was the fish most likely to escape during the surface hauling operation. The "tandem" cover experiments revealed a surprisingly high level of escape of fish at the surface. This probably results from a short fishing period (30 min) and the fact that, owing to the shallow fishing depth, the fish were in good condition when they reached the surface. Fish that escaped during bottom hauling were significantly smaller than fish that escaped at the surface. During the bottom hauling period, the meshes just in front of the catch are partly closed, and only small fish can escape. Larger fish, however, will have a better chance of escaping during surface hauling, when the covered codend is under low tension and the whole mesh lumen is available for escape. There is therefore great need for improvement of bottom selection (e.g. by grid systems), especially when fishing in deep waters.

The differences in selection factors between the PA and PE codends were not as clear as expected. For haddock, however, the PE codend gave a lower selection factor than the PA codend, a result that supports the fishermen's allegations of lower selectivity for heavy and stiff material. The tendency for the meshes in such material to close is regarded as greatest for new material, and the small differences found in this study may be explained by the fact that the PE codend used in this study had been in use for two years.

The selection factors obtained for cod and haddock in this study are somewhat higher than those given by Jakobsen (1983) using the ordinary covered codend method. However, the values found in these studies are much lower than the values obtained by the alternate haul method (Jakobsen, 1985) and by the trouser trawl method (Isaksen and Larsen, 1988). This difference in selection factor may be explained by the masking effect of the cover. The masking effect can be reduced to some extent by surface selection, in that fish kept back by the cover at the fishing depth may, as seen in this study, escape when the tension is taken off the covered codend. Such a reduction in the masking effect will depend on the condition of the fish when they reach the surface; therefore, when fishing in deep waters the reduction in the masking effect is less pronounced and the covered codend method is more biased.

However, the masking effect of the cover can be reduced or eliminated at the fishing depth by using hoops (Pope *et al.*, 1975). Nevertheless, as demonstrated by the "tandem" cover method, fish are capable of swimming out through the codend webbing at the surface, and may therefore also swim in the opposite direction into the codend again. The tendency to swim into the codend will probably increase with increasing quantities of fish in the cover. This effect may also cause bias in the results obtained by the covered codend method, and will be most pronounced when fishing in shallow waters, where fish are in good condition when brought to the surface. Selection parameters obtained by the covered codend method should therefore be handled with care, when fishing either in shallow or in deep waters.

Acknowledgements

We are grateful to the captains and crews of the participating vessels, especially for their good timing and quick responses to the different cycles of the operations.

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Behavioural studies of the principles underlying mesh penetration by fish

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The reactions of schools of fish to a narrowing funnel of netting were studied in a large swimming pool tank. The funnel was formed by two vertical frames each carrying a netting panel composed of large (400 mm or 240 mm) meshes or parallel strands of twine (200 mm or 120 mm apart). Test panels were constructed with twines presenting different visual contrasts when viewed against the horizontal water background. Results from experiments with schools of mackerel (*Scomber scombrus*, mean length 300 mm, school size 83–85) and haddock (*Melanogrammus aeglefinus*, mean length 200 mm, school size 65) show that, as they pass into the area of the funnel, a large proportion of the fish crowd through the central gap in the funnel, keeping clear of the walls even though they could easily pass through the large open meshes or parallel strands of twine. Panels with the strongest visual contrast were most effective at stimulating fish to keep clear, and both species were shown to be less willing to pass through horizontally orientated, parallel strands of twine than vertical ones. When attracted by conditioned feeding cues through the region occupied by the funnel, the fish were forced to choose either a short route through the meshes of the netting panel or a longer route through the gap of the funnel to receive the food reward. The proportion of fish passing through the panels increased in comparison with that during voluntary behaviour. Mackerel appear to be more willing to pass through the meshes than haddock. The experiments confirm that fish keep clear of netting panels and are reluctant to pass through large meshes. The use of visual contrast to induce fish to actively approach and attempt to pass through meshes is discussed.

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Introduction

Much recent research into selectivity of fishing nets concentrates on those properties of a net which are associated with selectivity as a mechanical function (for review see Anon., 1991). Current approaches towards improving selection include increases in mesh size or changes in mesh shape, both of which are designed to provide increased areas of open meshes through which fish are expected to pass. These approaches have been shown to change some of the mechanical selection characteristics of a net. However, it has been demonstrated over the last 30 years that selection is not achieved solely by mechanical means, and laboratory studies (Blaxter and Parrish, 1959, 1966; Mohr, 1961; Cui *et al.*, 1991) and observations made at sea show that behavioural reactions play an important role in the capture process (Blaxter *et al.*, 1964; Wardle, 1983, 1986, 1987, 1989; Glass and Wardle, 1989; Robertson, 1989). Fish have been observed to keep clear of the netting and are herded effectively by the panels of the wing-ends and the front regions of a net. Also, many fish entering the codend region of a net keep clear of the netting and do not attempt to pass through the open meshes surrounding them. Simply presenting the fish with larger openings, for example by increasing mesh size or inserting square mesh panels on the route to the codend, will not necessarily improve selectivity unless the fish attempt to pass through the meshes.

A codend cannot be effective unless every fish that enters the codend either attempts to penetrate the meshes or is passively brought into contact with them. This paper describes laboratory experiments which investigate the nature of the stimulus presented by netting panels and the role of fish behaviour in mesh penetration.

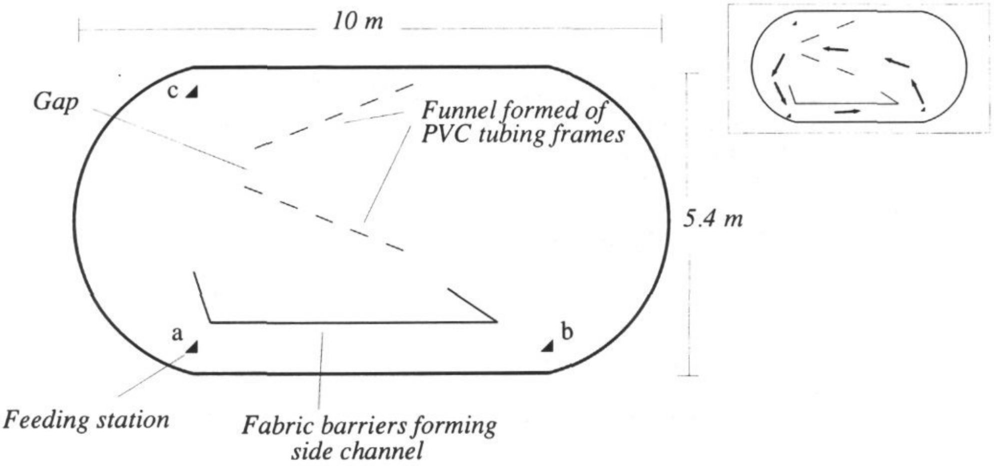

Figure 1. Plan diagram of the experimental tank, showing the position of the three feeding stations (a, b, c) and the arrangement of the barrier frames forming the test arena. The inset indicates the general pattern of movement of fish around the tank and the direction in which the fish were induced to swim during Phase 3 of an experiment.

Materials and methods

Experimental protocol

Schools of fish were established in large swimming pool tanks and separate studies were carried out on mackerel (*Scomber scombrus* L.) and haddock (*Melanogrammus aeglefinus* L.); mackerel were studied at Aultbea on the west coast of Scotland in a 10 m × 5.4 m × 1.3 m tank, and haddock at the Marine Laboratory, Aberdeen, in a smaller (7 m × 3.5 m × 1.3 m) similarly shaped tank (water depth was 1 m). The fish were acclimatized (for approximately 2 weeks) to an experimental arena as outlined in Figure 1 and were conditioned to race to a flashing light stimulus to obtain a food reward. The layout of the experimental tanks was similar at both sites and the movements of fish were continuously recorded on videotape by cameras mounted over the tank. Light intensity at the water surface in the light-tight experimental facilities was carefully controlled and maintained at 50–55 lx. For details of capture and transport arrangements, see Glass *et al.* (1986).

Each experiment consisted of three phases. In Phase 1 the fish were allowed to swim around the tank without obstruction. The general pattern of movement is illustrated in Figure 1 (inset). At a convenient moment when the fish were in the side channel out of sight of the main arena, the blank frames (2.4 m × 1 m) (Fig. 1) were substituted with similar frames strung with twine to form test panels (Phase 2). The behaviour of the fish in response to the netting stimulus (defined as voluntary behaviour) was recorded on videotape. Test panels were made of either knotless square mesh netting or strands of parallel twine orientated horizontally or vertically. Additional experiments (mackerel only) tested panels with parallel strands of twine sloping up or down with respect to the direction of swimming of the fish (Fig. 2). Phase 2 of an experiment lasted for approximately 20 min.

During Phase 3 the fish were induced to swim at higher speed from one feeding station to the next in the direc-

	Stimulus Configuration	Separation
Mackerel 300mm mean size	⊞ Square mesh	200mm
	≡ Horizontal twine	200mm
	⦀ Vertical twine	200mm
	// Twine sloping down towards gap	200mm
	\\ Twine sloping up towards gap	200mm
Haddock 200mm mean size	⊞ Square mesh	120mm
	≡ Horizontal twine	120mm
	⦀ Vertical twine	120mm

Figure 2. Details of the twine configurations used in each of the experiments. A separation of 200 mm between parallel twines was used in all experiments with mackerel, and 120 mm with haddock; for square mesh arrangements, this produced a stretched mesh equivalent to 400 mm (mackerel) or 240 mm (haddock). Each experimental configuration was carried out with black twine (1.8 mm diameter) and white twine (1.8 mm).

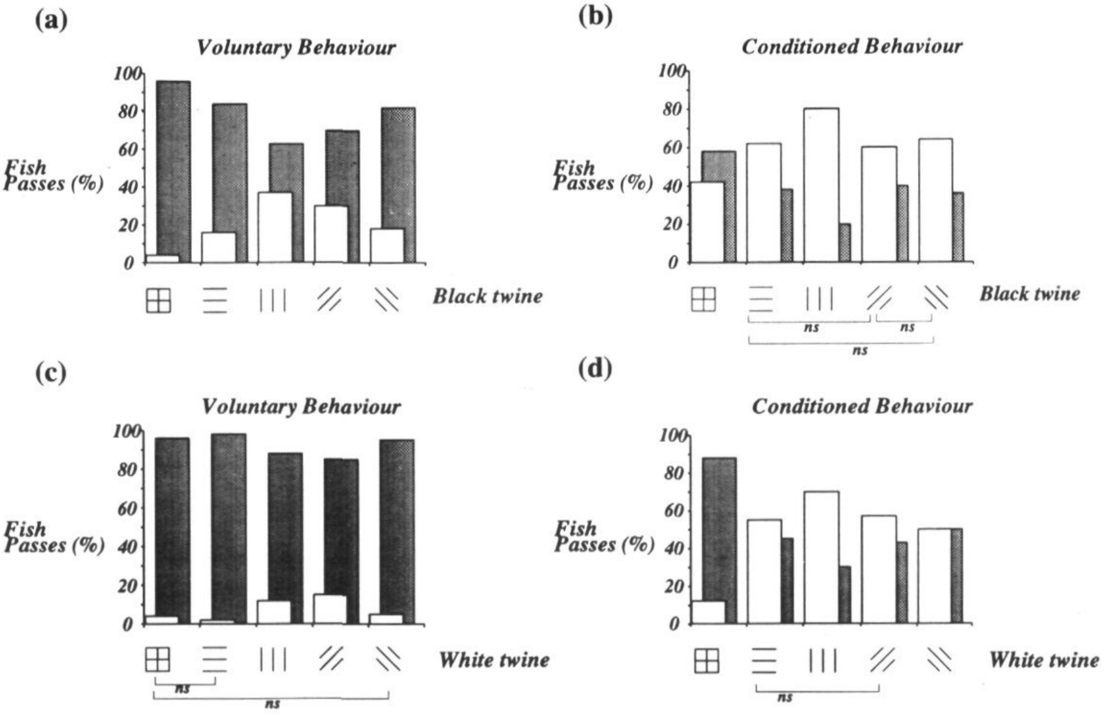

Figure 3. Summary of results from experiments involving mackerel. Each pair of bars represents the proportion of fish passing through the central gap (shaded bars) or the meshes of the funnel (open bars) for each of the twine arrangements and each of the twine types under test. Within each plot, the data presented in each pair of bars are significantly different ($p < 0.01$, χ^2 test on original data) from all others unless stated as not significant (ns).

tion outlined in Figure 1 (inset) (defined as conditioned behaviour) by an appropriate sequence of flashing the feeding cue lights (Fig. 1a, b, c). In addition to increasing the swimming speed of the fish, this presented the fish with a choice when swimming from feeding point b to feeding point c: feeding point c could be approached by passing directly through the netting panel or by a longer route through the gap. This phase of an experiment lasted for approximately 10 min. Barrier frames without twines (blank frames) were then substituted for the test frames and the fish were allowed to return to normal unobstructed passage round the tank. A further series of control experiments were carried out in which blank barrier frames were substituted for the blank frames, i.e. barriers without twine panels were used in the test condition (Phases 2 and 3). In order to prevent habituation to the test condition, only one experiment (i.e. all three phases) was carried out per day.

Experimental animals

Groups of 83 and 85 mackerel (mean length 300 mm approx.) were studied in 1990 and 1991 respectively, and reactions to a number of twine arrangements (Fig. 2) were noted. A group of 65 haddock (mean length 200 mm approx.) were subjected to a similar series of tests during 1991 (Fig. 2).

Details of test panels

The test panels (Fig. 2) were made of 1.8 mm diameter black twine or white twine and were selected to present different visual contrasts when viewed against the water background. Glow twine supplied by the Nichimo Corporation, Japan, was used as white twine. At the light intensities employed in this study, the luminescent property of the glow twine is not evident (Nakamura *et al.*, 1992) and the twine appears white. To human observers viewing the twines against the tank background under the experimental conditions, the white twine presented a higher-contrast stimulus than the black twine. Experiments with mackerel employed a twine separation of 200 mm, giving a stretched square mesh equivalent to 400 mm (200 mm bar length) (Fig. 2). For the smaller haddock a proportionately smaller twine separation gave a square mesh equivalent to 240 mm (120 mm bar length).

Analysis of data

Videotape of each experiment was analysed on a frame-by-frame basis. During each phase of an experiment the number of fish passing through the gap in the funnel (Fig. 1) was noted, as was the number of fish penetrating the frame barriers. Each is expressed as a proportion of the total number of fish passing through the test arena

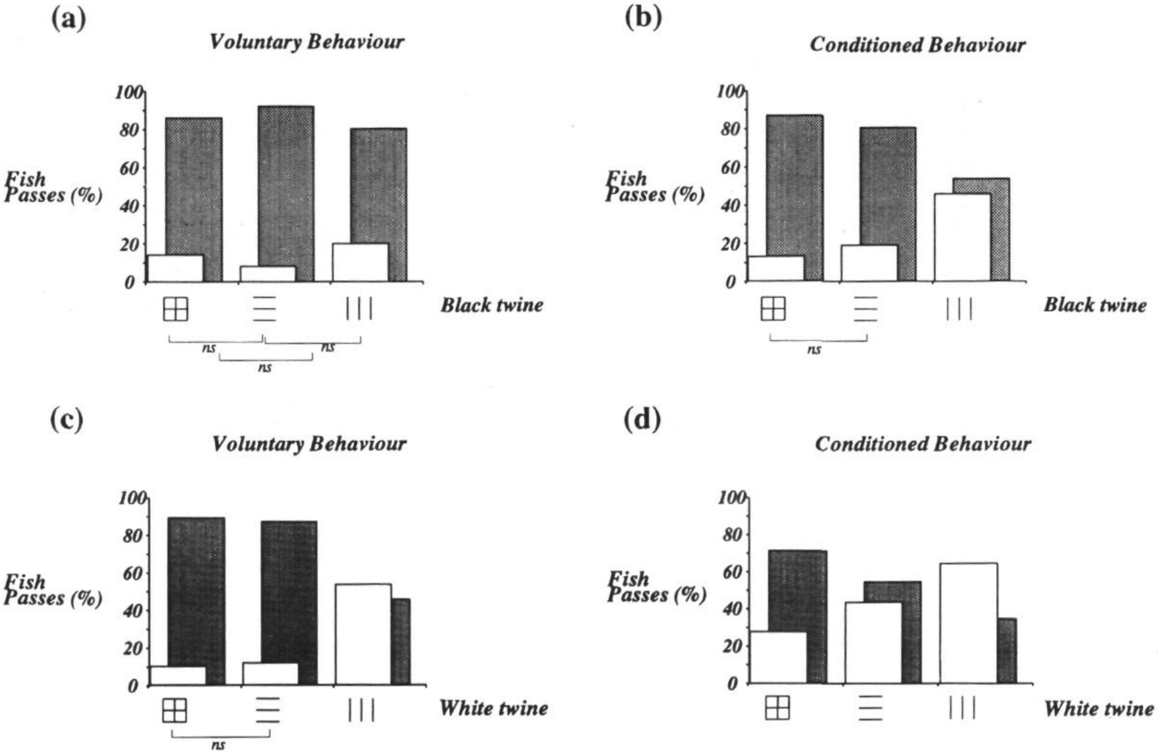

Figure 4. Summary of results from experiments involving haddock. Shaded bars represent the proportion of fish passing through the central gap and open bars the proportion of fish passing through the meshes of the funnel. Within each plot, the data presented in each pair of bars are significantly different (Fig. 4a; Fisher's exact test, $p < 0.01$: Fig. 4b, c, d; χ^2 test, $p < 0.01$) from every other unless stated.

during the complete phase. This forms a summary of the behaviour of the school of fish during each phase. Preliminary analysis indicated that the proportion of fish passing through meshes remained consistent for each pass of the school and that swimming speeds resulted in up to 50 passes by the school (mackerel) in a 20 min observation period.

Results

Figures 3 and 4 summarize data from experiments with mackerel and haddock respectively. Within each subfigure (a, b, c, d), the data presented in each pair of bars are significantly different from every other pair ($p < 0.01$, χ^2 test on original data, or Fisher's exact test for Fig. 4a) except those identified as not significant (ns). When allowed to swim through the test arena without any experimental manipulation (voluntary behaviour, Figs. 3a, c; 4a, c), most fish kept clear of the test panels and only a small proportion of the fish passed through the meshes. The pattern of response was similar for both species and, for a given species, for both of the twines under test. However, with mackerel, a greater proportion of fish approached and penetrated black twine than white twine, for each arrangement under test. This response was less evident in results of experiments involving haddock, where apart from parallel vertical twine arrangements, there was little evidence of a difference between black and white twine.

In Phase 3, when fish were induced to swim in response to flashing lights (conditioned behaviour, Figs. 3b, d; 4b, d), a greater proportion of fish passed through the twines (of all arrangements, and for both species) than during voluntary behaviour. As in Phase 2, the mackerel approached and penetrated black twine arrangements more readily than equivalent white twine arrangements. However, other than an increase in the proportion of fish penetrating the meshes, the overall pattern of response was similar to that displayed during voluntary behaviour. Haddock showed evidence of approaching and penetrating white twine more readily than black twine for each of the arrangements under test. The control experiments with blank frames in the test condition demonstrated no statistical difference in behaviour between Phases 2 and 3 for either species. This confirms that observed differences in behaviour are due to differential reaction to twine panels and not the presence of the barrier frames.

Within each group of tests, the results demonstrate that horizontal parallel twines were more effective at stimulating avoidance than vertical parallel twines. Parallel twines sloping upwards were also avoided more than twines sloping downwards along the direction of travel of the fish, and a greater proportion of fish approached and penetrated vertically orientated parallel twines than any other arrangement. At the other extreme, square mesh panels appeared to elicit the strongest avoidance.

Discussion

The results of these experiments demonstrate that the natural behaviour of the fish, as they pass into the area of a funnel of netting with an open gap, is to keep clear of the netting panel and pass through the gap. This natural avoidance response is emphasized by the fact that the fish could easily pass through the very large meshes (400 mm or 240 mm) or twine spacings (200 mm or 120 mm), openings which are much greater than those employed in many fishing gears at sea. It is also clear that the response is similar for two species which have quite different natural behaviour patterns (mackerel are an obligate schooling fish which swim constantly, whereas haddock are less active and form looser aggregations). These responses to the experimental funnel are similar to the herding and avoidance responses which occur in the mouth and forward parts of a trawl net fishing at sea (see Wardle, 1983, 1986, 1987, 1989 and Glass *et al.*, 1986). However, the results also demonstrate that the natural avoidance response shown in the laboratory can be modified by manipulation of the visual stimulus presented by the netting panel.

The results summarized in Figures 3 and 4 can be explained in terms of the different visual contrasts that the twine arrangements present when seen by the fish against the water background. The square mesh panels have both a vertical and a horizontal component and present a stronger visual stimulus than parallel twine panels. Consequently, the square mesh panels elicit the strongest avoidance response. When the square mesh is split into its constituent horizontal and vertical components, the avoidance response is reduced, but significant differences are also apparent in the reactions of the fish to each component. Recent research (Wardle *et al.*, 1991; see also Wardle, 1986) has shown that the visibility or appearance of a twine varies according to its colour and angle relative to the water surface. It has also been shown that horizontally orientated twines present a stronger visual stimulus than vertically orientated twines, owing in part to reflection of downwelling light off the upper surface of the horizontal strands. Horizontal twine might therefore be expected to elicit a stronger avoidance response than vertically orientated twine; the results show this to be the case. The same is true for diagonally sloping twine. The upper surface of twine sloping up with respect to the direction of swimming of the fish would be expected to reflect a greater degree of downwelling light in the direction of an approaching fish than twine sloping down away from the fish. Twine sloping up therefore presents a different (stronger) contrast with the horizontal background against which it is viewed and might be expected to elicit a greater avoidance response than twine sloping down. Horizontal twine presents a stronger contrast than sloping twine and would be expected to elicit the strongest avoidance response of any of the parallel twine arrangements. In addition, for any given twine arrangement, a change in contrast by changing the twine type results in an observed change in behavioural reaction to the panel under test. For example, in the experimental setup used in this study, mackerel will approach and penetrate twine arrangements constructed of black twine more readily than equivalent arrangements of white twine, but the degree of approach and penetration depends on the nature of the twine arrangement under test.

The results demonstrate that fish avoid the more visible twine arrangements, and the weaker the contrast of the twine with the background, the more likely fish are to approach and penetrate the meshes. It is also clear that the movements of fish can be manipulated by appropriate modification of the stimulus surrounding the fish. Observations made at sea suggest that fish must be stimulated to change their natural reaction from keeping clear of meshes to approaching and attempting to pass through them. The present study and studies such as those of Cui *et al.* (1991) and Wardle *et al.* (1991) demonstrate that the natural behaviour of fish can be altered by subtle changes in the surrounding visual stimulus. By careful consideration of the behaviour patterns shown by fish to surrounding panels of netting and by identification of the important components of the overall visual stimulus, it may be possible to create a system of visual illusions within a fishing net, which would stimulate fish to approach and even penetrate meshes more readily. Such a system might be applied to improve selection characteristics.

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Three tentative approaches to modelling fish behaviour in relation to fishing gears

Nobuo Sannomiya and Ko Matuda

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In order to clarify the effect of fishing gears on fish behaviour, this paper reviews some results obtained by systems engineering approaches such as mathematical modelling and computer simulation. Any mathematical model is usually constructed on the basis of a hypothesis or some assumptions. Balchen proposed a fish behaviour model under the assumption that a fish moves at any time so as to maximize a comfort function defining a field of stimuli. Sannomiya and Matuda proposed another fish behaviour model, which differs from Balchen's model in the assumption that a fish moves under the influence of several external forces. Miura investigated the path of fish approaching a set net by modelling an interaction between fish and a gear space as an m-th order of Markov source.

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Introduction

Fish behaviour has been examined by underwater visual observation. It is difficult, however, to clarify the principle of fish behaviour using only the traditional methods of fisheries science. If some of the approaches developed in systems engineering are applicable as an effective means of data processing and analysis of this problem, the results obtained may be expected to provide useful suggestions for considering this problem. In systems engineering, computer simulation techniques are used for analysis, design, and planning, not only of technical but also of non-technical systems. For this purpose, we need to construct a mathematical model for describing the systems considered.

This paper presents recent developments in mathematical models of fish behaviour in relation to fishing gears. In particular, the work done by Balchen (1979, 1981), Sannomiya and co-workers (1984, 1987, 1990), and Miura (1986) are introduced.

Model developed by Balchen

Balchen (1979, 1981) proposed a model for estimation and control of fish behaviour. His model is based on the following assumptions: (1) Fish movement is a result of an interaction between the biological state of the fish and the environmental state. (2) A fish moves at any time so as to maximize a comfort function defining a field of stimuli.

Thus, the fish behaviour model is given by

$$\dot{x} = f(x,v,|\dot{r}|,t) \tag{1}$$

$$\dot{r} = \partial C(x,v)/\partial r \tag{2}$$

where x is the biological state vector of fish, v is the environmental state vector, and r is the vector of fish position.

In Equation (1), the function f is determined from elementary physiological principles. The function C in Equation (2) is called the comfort function, which is expressed mathematically as a scalar field. Usually, C is given as an additive form, each term of which depends on one or more of the environmental state variables, such as temperature, food concentration, or light intensity.

By using this model, Balchen proposed several schemes for active control of fish behaviour. The active control can be achieved by generating and transmitting artificial stimuli that either attract or repel the fish. In the case of a fishing gear, the comfort function C for the gear must be constructed. It is difficult, however, to determine the forms of f and C, especially as no explicit form of C for fishing gears has yet been proposed.

Model developed by Sannomiya and Matuda

Sannomiya and Matuda (1984, 1987) and Sannomiya *et al.* (1990) developed another fish behaviour model. The model is based on the assumption that fish move under the influence of several external forces. A school is assumed to consist of N_f fish. Let x_i be the position vector of the individual i in the school. Then, the motion of N_f individuals in the school is described by

$$m\ddot{x}_i(t) = F_i(t,x_i,\dot{x}_i,x_j,\dot{x}_j) + \xi_i(t) \qquad i,j = 1,2,\cdots,N_f;\ i \neq j \tag{3}$$

where m is the mean mass of the individuals. In Equation (3), F_i and ξ_i are the external force and the disturbance for the motion of the individual i, respectively.

The functional form of F_i is assumed by considering the main causes of fish motion. It consists of three components which are determined by referring to several observational results (Breder, 1959; Shaw, 1970; Radakov, 1973; Partridge, 1982). Each component is given as follows.

An individual fish has a character of swimming forward according to its own swimming ability and the damping effect exerted by the ambient water. The first component of F_i is expressed by

$$F_{i1} = a_i\dot{x}_i/\|\dot{x}_i\| - \nu\|\dot{x}_i\|\dot{x}_i \tag{4}$$

where $\|\cdot\|$ is the Euclidean vector norm. In Equation (4), the first term is the propulsive force and the second term is the damping force. The parameter a_i is called the propulsive coefficient of the individual i. The parameter ν is a drag parameter and is given by

$$\nu = 0.5\,\rho\,C_D A \tag{5}$$

where ρ is the density of water, C_D is the dimensionless drag coefficient of fish (≈ 0.1), and A is the largest cross-sectioned area of the fish normal to the stream.

An individual fish has a character of behaving under the influence of motion of other fish. The second component of F_i is given by

$$F_{i2} = \sum_{j=1}^{N_f} b_i(r_{ij})\frac{x_j - x_i}{r_{ij}} + \sum_{j=1}^{N_f} c_i(r_{ij})\frac{\dot{x}_j - \dot{x}_i}{N_f} \tag{6}$$

where $r_{ij} = \|x_i - x_j\|$. In Equation (6), the first term is the interactive force and the second term is the schooling force. The interactive force expresses the character of keeping a proper distance between neighbouring individuals. The form of $b_i(r_{ij})$ should be chosen so that the repulsion acts on the individual i for small r_{ij} and the attraction acts for large r_{ij}. The schooling force is introduced to express the character of uniforming the swimming speed and the swimming direction in the school. The form of $c_i(r_{ij})$ should be chosen so that the schooling force acts only between the individuals existing within a critical distance. The detailed expressions for b_i and c_i are omitted here (see Sannomiya *et al.*, 1990).

An individual fish receives a certain stimulus from the environment. In the case of fishing gears, the wall of the gear affects fish motion. One effect is to attract the fish, and the other is to repel the fish. Then, we have as the third component of F_i:

$$F_{i3} = k_{wi}^{+}\sum_{l=1}^{L} f_{wil}^{+} + k_{wi}^{-}\sum_{l=1}^{L} f_{wil}^{-} \tag{7}$$

$$f_{wil}^{+} = \begin{cases} v_{il}e_l(d^+ - d_{il})/d^+ & \text{for } v_{il} > 0 \text{ and } d_{il} < d^+ \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

$$f_{wil}^{-} = \begin{cases} v_{il}e_l(d^- - d_{il})/d^- & \text{for } v_{il} < 0 \text{ and } d_{il} < d^- \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

where L is the number of the wall sides. The unit vector e_l is normal to the wall l, and v_{il} is the velocity component normal to the wall l, being given by $v_{il} = -e_l^T\dot{x}_i$. The quantity d_{il} is the distance from the individual i to the wall l. The critical distances are denoted by d^+ and d^-. In Equation (7), the first and the second terms are the repulsive and the attractive forces from the wall, respectively. The parameters $k_{wi}^{+}(>0)$ and $k_{wi}^{-}(>0)$ are their coefficients. The repulsive force acts when the individual approaches the wall ($v_{il} > 0$), and the attractive force acts when it goes away from the wall ($v_{il} < 0$). Both forces act when the individual is located near the wall ($d_{il} < d^+$ or $d_{il} < d^-$).

In Balchen's model, the effect of fishing gears is given by the gradient of some comfort function. On the other hand, in our model it corresponds to F_{i3}, the functional form of which is easily determined in terms of several parameters.

In Equation (3), we introduce the disturbance ξ_i in order to express causes for the motion other than those mentioned above, such as abnormal movement due to the psychological state of fish.

The unknown parameters included in the model were estimated from water tank experiment data. The video image data were sampled at the intervals of $\Delta t = 0.5$ s. The position of each individual fish was calculated at every discrete time by using an image processor and a personal computer. From the time-series data of fish position, the unknown parameters were estimated by applying the least squares algorithm (Sannomiya and Matuda, 1987).

Water tank experiments of fish behaviour related to model nets were made with a variety of trap configurations. The corresponding computer simulation was executed on the basis of the model given by Equations (3)–(9). The calculation was carried out by using the discrete-time form for these equations. Random numbers were assigned for the values of ξ_i and $x_i(0)$. The parameters were given by

$$N_f = 3,\ m = 2.58\ \mathrm{g},\ a_i = 2.14\ \mathrm{g{\cdot}cm/s^2},\ \nu = 0.01\ \mathrm{g/cm},\ k_{wi}^{+} = 5.37\ \mathrm{g/cm},\ k_{wi}^{-} = 1.13\ \mathrm{g/cm},\ d^{+} = 10\ \mathrm{cm},\ d^{-} = 20\ \mathrm{cm} \tag{10}$$

Figure 1 shows a comparison of fish trajectory between the experiment and the simulation for the single-mouth trap with two bags. Figure 2 shows the time variation of the proportion R(t) of members of the fish school remaining in the trap up to time t, which is the result of fifty simulation trials. For other simulation results, see Matuda and Sannomiya (1985).

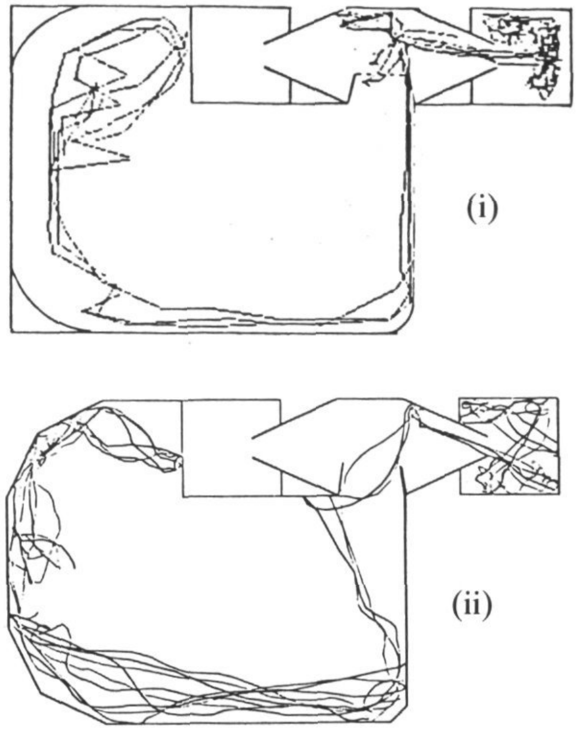

Figure 1. Comparison of school behaviour between an experiment and a simulation for the case of a single-mouth trap with two bags: (i) experimental result; (ii) simulation result.

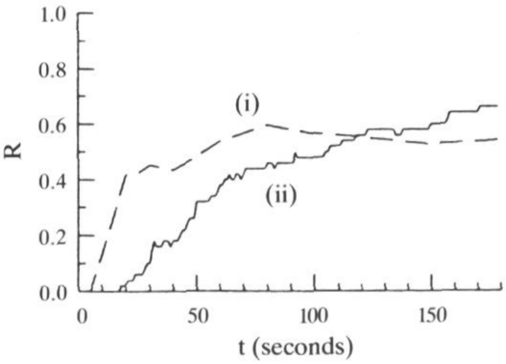

Figure 2. Time variation of the proportion of fish remaining in the case of single-mouth trap with two bags: (i) experimental result; (ii) simulation result.

Model developed by Miura

Miura (1986) proposed a stochastic model for investigating the interaction between fish and gear space without using any artificial stimuli. As shown in Figure 3, the model consists of two subsystems, fish and gear space. In this model, we consider that the gear space stimulates a fish and consequently the fish enters a set net. The fish is assumed to be an information-processing system which transforms interactions with the gear space into sequential events. Fish behaviour is considered to be a process of zone selection in the gear space.

Thus, fish and gear space are described as a threefold Markov source. In this case, a zone s_r of space is connected to the preceding zone and the succeeding zone along the swimming path. The average entropy value for the zone s_r is given by

$$I(s_r) = -\sum_{j=1}^{n}\sum_{i=1}^{n} P(q_j,s_i)\log_2 P(s_i|q_j) \tag{11}$$

where n is the number of zones, q_j is a state describing the preceding path, i.e. $q_j = s_j,s_r$ (s_j is the preceding zone), and s_i is the succeeding zone.

As a consequence of water tank experiments done by Miura, it was observed that the zone at the exit point of

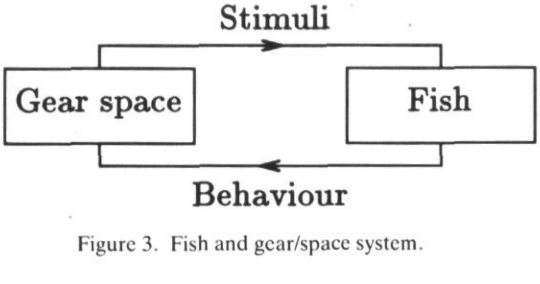

Figure 3. Fish and gear/space system.

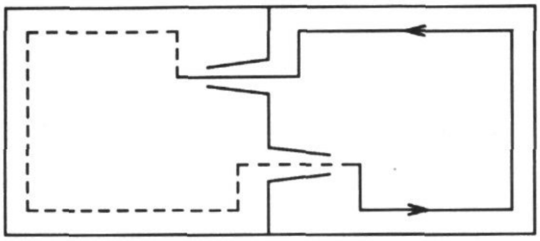

Figure 4. The common trajectory for various fish schools.

the funnel of the gear has high entropy value. On the other hand, the zone at the funnel itself has zero entropy value. Figure 4 shows the common trajectory for various fish schools obtained by entropy evaluation. Figure 5 shows the relationship between the number of individual fish in a school and the total entropy value along the common trajectory. A single fish has high entropy value, owing to its random movement along the wall. On the other hand, a school of eight fish has low entropy value, owing to schooling effect.

Discussion and concluding remarks

Three kinds of fish behaviour model have been introduced. They may be compared as follows.

1. Balchen's model is based on the striking idea of the comfort function. However, the construction of the comfort function is difficult for the case of fishing gears. In Sannomiya and Matuda's model, several external forces are proposed instead of the comfort function. The construction of the functional form of the external force is relatively easy.
2. Miura's model is used not for simulation but for analysis. In fact, his model describes in detail the relationship between fish and gear space. Therefore, the result of analysis is useful for the construction of F_{i3} in the Sannomiya–Matuda model.

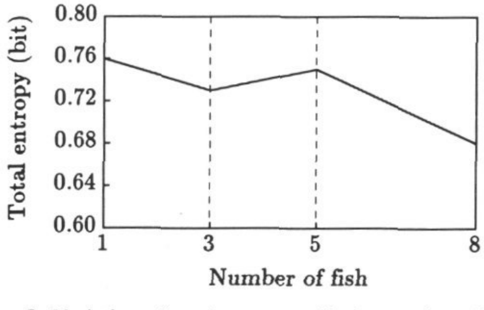

Figure 5. Variation of total entropy with the number of individual fish in a school.

3. As shown in Figure 5 of Miura's result, the schooling effect is important in fish behaviour relevant to fish capture processes. In the Sannomiya–Matuda model, this effect is expressed mathematically by F_{i2} in Equation (6). This schooling force models the exchange of information which an individual fish receives from other members in a school. An interesting result has been obtained by a simulation carried out from this viewpoint. We change Equation (6) into the following form:

$$F_{i2} = \sum_{j \in N(i)} b_i(r_{ij}) \frac{x_j - x_i}{r_{ij}} + \sum_{j \in N(i)} c_i(r_{ij}) \frac{\dot{x}_j - \dot{x}_i}{M} \qquad (12)$$

where N(i) is the set of individuals existing near individual i. The number of the members in N(i) is M, where $1 \leq M \leq N_f - 1$. Then, simulation results show that the school size varies with M, but the average speed of a school does not vary significantly with M. In addition, an individual fish does not need the exchange of information from all members in a school in order to match its speed and direction. An example of simulation shows that 20 fish ($N_f = 20$) makes a school when $M = 4$.
4. When a fish school moves, its shape, size, and other characteristics may vary at any moment. These variations are considered to be due to many causes, such as environment or fish psychology. It is interesting to conjecture that these variations are also due to variation in the value of M. That is, the value of M depends on the biological state of the fish, which is affected by environmental or other random factors. This suggests the integration of the Sannomiya–Matuda model and Balchen's model.

On the basis of the above discussion, we summarize how to apply these three models.

1. By using Miura's model, the wall effect on fish behaviour is analysed and the common trajectory of a fish school encountering fishing gear is obtained. Consequently, the functional form of F_{i3} in the Sannomiya–Matuda model is constructed by estimating the distances d^+ and d^-.
2. The Sannomiya–Matuda model is constructed on the basis of observational data. The functional form of F_{i2} should be given by Equation (12), instead of Equation (6). In this case, it is an open question to decide the relationship between the value of M and the biological state of fish.
3. The construction of the model for describing the biological state of fish, i.e. Equation (1) in Balchen's model, is also an unknown subject.

Therefore, the three models are not opposing concepts, but should be unified as a single model. In other words, the Sannomiya–Matuda model and Miura's model demonstrate how to construct the comfort function of Balchen's model.

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Comparison among fish species of parameters in a fish behaviour model

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Matuda, K., Liang, Z., and Sannomiya, N. 1993. Comparison among fish species of parameters in a fish behaviour model. – ICES mar. Sci. Symp., 196: 103–107.

A physical model is presented to describe the behaviour of fish in a water tank. A system equation which includes several non-linear terms representing the main functions for fish motion is introduced. The model parameters are estimated by applying a least-squares algorithm. Using data from observations of four fish species (Japanese dace, rainbow trout, carp, and tilapia) maintained in an equilateral octagonal water tank, the parameter values included in the behaviour model are estimated and compared among different species. The validity of the model is investigated by testing the whiteness of the residual of the state equation and by comparing the simulation result with the experimental result. There were no appreciable differences among species in the parameters of the interactive force, schooling force, and repulsive force against the wall, whereas a big difference among species was observed in the propulsive force parameter.

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Introduction

Fish behaviour studies in relation to fishing gears have been conducted by Matuda and Sannomiya (1980) and Sannomiya and Matuda (1987) using time-series data obtained from water tank experiments. From these studies they proposed methods to model and simulate fish behaviour. However, they only used bitterling (*Rhodeus ocellatus ocellatus*) as a fish species, and more recently, Liang *et al.* (1992) used Japanese dace (*Tribolodon hakonensis*) to model behaviour.

This paper deals with a parameter estimation and computer simulation of a behavioural model using four fish species, namely Japanese dace, rainbow trout (*Oncorhynchus mykiss*), carp (*Cyprinus carpio*), and tilapia (*Tilapia mossambica*), in an octagonal tank.

Description of the model

The motion of an individual fish can be regarded as that of a particle in a three-dimensional space. However, for simplicity, we have assumed that the motion is restricted in a two-dimensional space. Then, the movement of the individual i in the school of N_f fish is described by:

$$m\ddot{x}_i = F_i(t,x_i,x_j,\dot{x}_i,\dot{x}_j) + \xi_i(t) \tag{1}$$

$$i,j = 1,2,3,\ldots,N_f;\ i \neq j$$

where x_i is the position vector of the individual i, $\dot{x}_i$ is the velocity vector, m is the mean mass, F_i is the external force acting on the individual i, and ξ_i is a disturbance. It is assumed that the force F_i consists of three components, the propulsive and damping force F_{i1}, the interactive force F_{i2} acting from the other members of the school, and the environmental force F_{i3}. Based on the results of the study, the following functional forms of these forces are obtained as

$$F_{i1} = a_i\dot{x}_i/\|\dot{x}_i\| - \nu\|\dot{x}_i\|\dot{x}_i \tag{2}$$

$$F_{i2} = k_{bi}\sum_{j=1}^{N_f} b_i(r_{ij})\frac{x_j - x_i}{r_{ij}} + k_{ci}\sum_{j=1}^{M_i} c_i(r_{ij})\frac{\dot{x}_j - \dot{x}_i}{M_i} \tag{3}$$

$$b_i(r_{ij}) = \frac{2(r_{ij}/\alpha - 1)}{(r_{ij}/\alpha - 1)^2 + 1} \text{ for } r_i \leq \beta \tag{4}$$

$$c_i(r_{ij}) = \begin{cases} [1 - ((1 - \cos \pi r_{ij}/\delta)/2^2] & \text{for } r_{ij} \leq \delta \\ 0 & \text{for } r_{ij} > \delta \end{cases} \tag{5}$$

$$F_{i3} = k_{wil}\sum_{l=1}^{L} f_{wil} \qquad (6)$$

$$f_{wil} = \begin{cases} v_{il}\dfrac{d - d_{il}}{d}e_l & \text{for } v_{il} > 0 \text{ and } d_{il} < d \\ 0 & \text{for otherwise} \end{cases} \qquad (7)$$

Here,
v: drag parameter of individual i
$\|\dot{x}_i\|$: the Euclidean vector norm
L: number of walls of the tank
d_{il}: distance between individual i and wall l
e_l: unit vector normal to the wall
v_{il}: velocity component of individual i normal to the wall
r_{ij}: distance between individual i and individual j
M_i: number of individuals existing within the circle of radius δ the centre of which is individual i

The first component F_{i1} represents a character of swimming forward according to its own swimming ability and the damping effect exerted by the water. In Equation (2), the first term is the propulsive force, and the second term is the damping force. The second component F_{i2} expresses a character of behaving under the influence of the motion of other fish. The first term of Equation (3) is the interactive force between individuals, and the second term is the schooling force. The interactive force between individuals acts to maintain a constant distance from one individual to another. The form of $b_i(r_{ij})$ in Equation (4) is decided in such a way that the repulsive force acts on the individual i when the distance r_{ij} to the individual j is smaller than α, and the attractive force acts when it is larger than α within the critical distance β. The form of $c_i(r_{ij})$ in Equation (5) is decided in such a way that the schooling force acts only between individuals existing within the critical distance δ. The third component F_{i3} in Equation (6) represents certain stimuli from the environment, such as walls. The more detailed expressions for the mathematical model are omitted here (see Matuda and Sannomiya (1980) and Sannomiya and Matuda (1993)). The values of the parameters m, ν, d, α, β, δ are taken from experimental data. The unknown parameters a_i, k_{wi}, k_{bi}, k_{ci} are estimated using the observed data for the swimming trajectories of individual fish.

Materials and methods

Figure 1 shows the set-up of the apparatus used in the experiment. The experiment was carried out in an octagonal tank measuring 1.7 m on each side. The tank was located inside a 6 m × 6 m × 3 m dark room and illuminated by four spot lights located in the corners of the room. Four TV cameras were suspended from the ceiling and connected to a video cassette recorder (VCR) located outside the dark room, and thus all observations of fish behaviour were made from outside the dark room. Care was taken to prevent any unnecessary stimulus, such as the sound of the VCR or the presence of an observer, which might influence the normal behaviour of the fish. Light intensity in the dark room was maintained at 135 lx for all experiments.

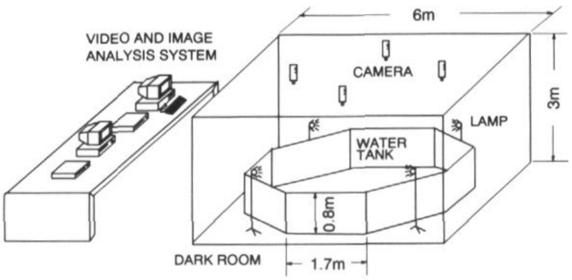

Figure 1. Schematic diagram of experimental apparatus.

Four species of fish were used: rainbow trout, tilapia, carp, and Japanese dace. Aside from dace, all fish were reared in a tank since hatching. Five fish for each species having similar body weight and length were used for every set of observations. The mean body length and weight of fish used and the other experimental conditions are given in Table 1.

The experiments were carried out between April and July, 1991. Fish were released into the tank one week prior to the commencement of an experiment to stabilize their behaviour, which was observed to be erratic immediately after they were released into the tank. After the behaviour of the school had stabilized, the experiment was carried out. The same environmental conditions were maintained for all observations and any species. The number of fish was varied for each observation and ranged from one to five fish.

A waiting interval of 30 min was left between successive observations. The behaviour of the school was observed during 10 min and was recorded on a VCR. The depth of water was 15 cm.

From images recorded on the VCR, the positions of the fish at each sampling period were calculated by using

Table 1. Summary of experimental conditions.

Fish species	Mean length* (cm)	Mean weight* (g)	Water temperature (°C)	Experimental date
Rainbow trout	18.0	67.6	16.3	24 Apr 1991
Tilapia	20.7	162.8	18.3	11 May 1991
Japanese dace	10.4	13.3	22.0	7 Jun 1991
Carp	14.5	58.8	28.3	31 Jul 1991

* Mean values for five individuals.

a personal computer image analyser system (PIAS LA-525). One sampling interval for each calculation was about 0.5 s (equivalent to 1 frame movement of the VCR), giving a data set of about 1200 positions for each fish (10 min duration/fish).

Results and discussion

Parameter estimation

The parameters m, ν, d, α, β, and δ were obtained from measurements and observations during the experiment (Table 2). Using the data obtained for the four species, the parameters (a_i, k_{wi}, k_{bi}, k_{ci}) were estimated by least-squares parameter estimation (Sannomiya and Matuda, 1987). As an example of the results, the parameter values for rainbow trout are given in Table 3. (Hereafter, owing to page number limitations, only the results for rainbow trout are given as an example.)

Almost all the estimated values of parameters were positive with little variation. However, negative values were obtained for the propulsive force parameter of some individuals in a tilapia school. This may be taken to indicate that the swimming behaviour of tilapia is not active compared with that of the other species. Tilapia is characterized by sometimes swimming backward for a short period, and this unpredictable behaviour of tilapia is considered to be the cause of the negative value in the propulsive force parameter.

In order to confirm the validity of the mathematical model, the whiteness test for residuals of the state equation was examined for each fish species according to the method of Sannomiya and Matuda (1987). It follows from this test that the validity of the mathematical model is satisfied at the 95% confidence level for all species.

Simulation results

In this section, the validity of the proposed model is examined by comparing the experimental results with the corresponding simulation results. The experimental results were obtained from the water tank experiment. The corresponding computer simulation was executed on the basis of the mathematical model proposed here. The computer calculation was carried out by replacing Equation (1) with the associated discrete-time system. The value of N_f was set to be from one to five, and the same boundary condition as in the equilateral octagonal water tank was specified.

Comparisons between the experiment and simulation for an individual in a school of three rainbow trout are shown as an example in Figures 2–4. Figure 2 is a comparison of the swimming trajectory, Figure 3 is the time-series variation of the swimming speed, and Figure 4 is the nearest distance between fish. As can be observed from these figures, there is a close resemblance between the simulation and the water tank experiment.

Comparison of non-dimensional parameters

Since the parameter values, estimated previously, vary depending on the body size of the fish, we need to convert them to dimensionless forms so that their differ-

Table 3. Estimated values of parameters for rainbow trout.

Number of fish	No.	Parameters			
N_f	i	a_i	k_{wi}	k_{bi}	k_{ci}
1	1	366.	61.5	—	—
2	1	118.	54.4	183.	5.7
	2	305.	76.7	466.	41.9
3	1	84.	118.0	260.	27.7
	2	62.	59.9	143.	12.7
	3	46.	69.2	96.	10.6
4	1	186.	48.0	179.	18.7
	2	110.	72.1	139.	25.7
	3	168.	73.2	161.	33.7
	4	177.	91.1	118.	25.8
5	1	135.	32.6	167.	18.4
	2	245.	44.4	191.	24.1
	3	99.	32.2	205.	18.5
	4	142.	43.3	168.	22.2
	5	291.	39.4	208.	19.8
Mean value		169.	61.1	192.	21.8
s.d.		91.	22.6	86.	8.9

Table 2. Values of known parameters.

Fish species	m (g)	ν (g/cm)	α (cm)	β (cm)	δ (cm)	d (cm)
Rainbow trout	67.7	0.31	25	150	150	150
Tilapia	162.8	0.84	20	150	150	150
Japanese dace	13.3	0.11	12	150	150	150
Carp	58.8	0.41	8	150	150	150

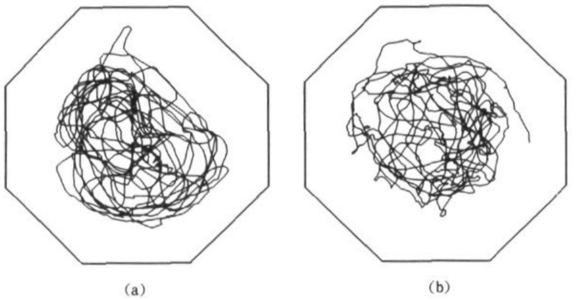

Figure 2. Comparison of the swimming trajectory for rainbow trout between (a) experiment and (b) simulation.

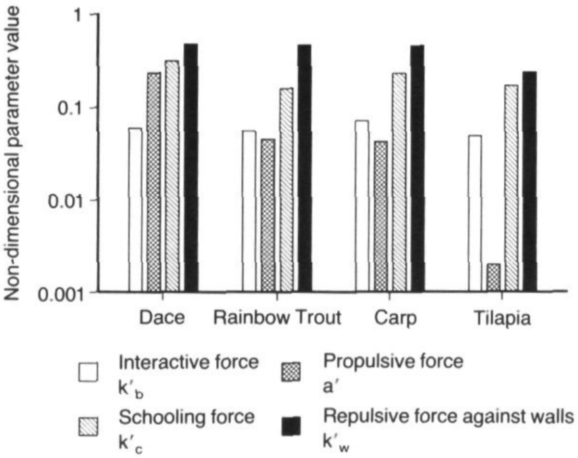

Figure 5. Comparison of the non-dimensional parameter values among the four fish species used in the experiment.

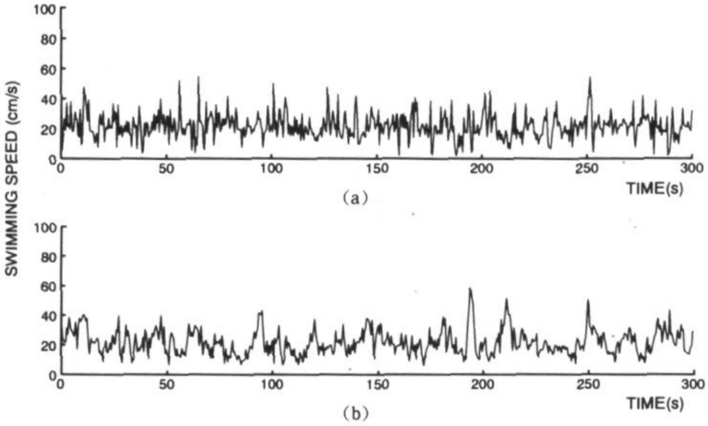

Figure 3. Comparison of the time variation of the swimming speed for rainbow trout between (a) experiment and (b) simulation.

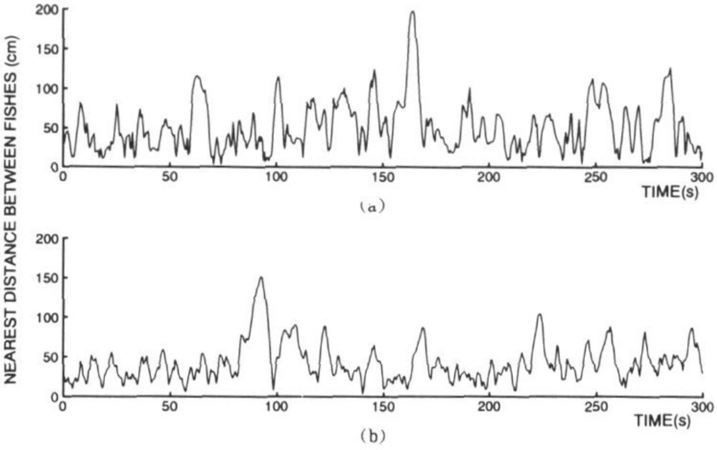

Figure 4. Comparison of the nearest distance between individual rainbow trout in the school between (a) experiment and (b) simulation.

ences among species can be compared. The nondimensional parameters can be defined as follows,

$$\left.\begin{aligned} a' &= a \cdot \Delta t/(m \cdot \bar{v}) \\ k'_w &= k_w \cdot \Delta t/m \\ k'_b &= k_b \cdot \Delta t/(m \cdot \bar{v}) \\ k'_c &= k_c \cdot \Delta t/m \end{aligned}\right\} \quad (8)$$

where m is mean body mass, $\bar{v}$ is mean swimming speed of fish, and Δt is the sampling time ($\Delta t = 0.5$ s). The parameters a, k_w, k_b, and k_c represent the mean values of the estimated values of the respective parameters a_i, k_{wi}, k_{bi}, and k_{ci}.

The parameter values obtained by using Equation (8) for each species are shown in Figure 5. There were no significant differences among the four species in the values of the parameters k'_w, k'_b, and k'_c, whose values ranged as follows: $k'_w = 0.23 \sim 0.47$, $k'_b = 0.05 \sim 0.07$, and $k'_c = 0.16 \sim 0.32$. On the other hand, big differences were observed for the propulsive force parameter a'. A relatively high value (a' = 0.24) was observed for dace, a low value (a' = 0.002) for tilapia, and the values for rainbow trout and carp were on or near the median. This suggests that the propulsive force plays a substantial role in controlling the behaviour of a fish school. Further, the parameter of repulsive force against the wall was shown to be higher than the other parameters.

In conclusion:

1. The parameters included in a mathematical model for describing fish behaviour were estimated by using observational data from water tank experiments. The least-squares algorithm was applied for parameter estimation of the mathematical model. The validity of the model was proved statistically by means of the whiteness test of the residual. A satisfactory result was also obtained for the computer simulation.
2. No appreciable difference was detected among species in the parameter values of the interactive force, the schooling force, and the repulsive force against the wall. However, a big difference among species was observed in the propulsive force parameter. The highly active dace had a large value, and the less active tilapia a small value. It follows from this result that the propulsive force parameter is consistent with the swimming activity of the fish in the water tank.
3. It seems probable that the parameter of the repulsive force against the wall has higher values than the other parameters, such as the schooling force and the interactive force between fishes. In order to apply the mathematical model to improve fishing gears, we need to carry out experiments so that the parameter representing the influence of the netting wall on fish behaviour can be estimated.
4. The number of parameters in the model should be as small as possible, both for executing computer simulations based on the mathematical model, and for applying the mathematical model to fishing gears. It should be appreciated that this model passed the whiteness test notwithstanding the lower number of parameters in this model than in other models (Sannomiya and Matuda, 1984; Sannomiya *et al.*, 1990a; Sannomiya *et al.*, 1990b).
5. These results suggest the applicability of the model to the improvement or the optimum arrangement of set nets. However, a long-term approach may be needed before applying this model to real fishing gears.

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Detection and reaction of fish to infrasound

Per S. Enger, Hans Erik Karlsen, Frank R. Knudsen, and Olav Sand

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Hearing in fish has until a few years ago been considered to cover a sound frequency range from 20–30 Hz up to below 1000 Hz in most species. It is now known that the frequency spectrum extends down in the infrasound range (below 20 Hz). For cod, plaice, perch, roach, and salmon, hearing thresholds have been established by a conditioning technique for sound frequencies down to below 1 Hz. Tests on the behavioural reaction to sound in juvenile salmon have been performed in a large tank. Infrasound (10 Hz) produced spontaneous avoidance responses, while no such responses could be seen at 150 Hz. Tests on down-river migrating salmon smolts have also been performed. During a stimulation period of 170 min, only six fish passed the operating 10 Hz sound source, whereas 338 fish passed during a silent period of the same duration. The 150 Hz stimulation had no evident effect on the migration.

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Introduction

The audible sound frequency range of fish has been investigated for a number of species. Roughly speaking, all species perceive sound in the low frequency range up to several hundred Hz, while some, notably the clupeoids and the ostariophysean species, have an upper limit of 4000–7000 Hz. The latter groups have a particular anatomical structure connecting the swimbladder to the inner ear.

All fish audiograms have the lowest threshold below 1000 Hz. Measured as sound pressure, the lowest values are in the 100–200 Hz range in the non-specialized species. An extensive list of fish audiograms has been given by Fay (1988). None of them includes threshold values for frequencies below 20 Hz.

Until a few years ago, little interest was paid to the possible reception of infrasound (below 20 Hz). One reason for this was simply that auditory thresholds increased toward both higher and lower frequencies from a middle range of highest sensitivity. However, this was because the threshold values were plotted as sound pressure, which is not the appropriate stimulus for the auditory hair cells. These cells cannot be stimulated by pressure variations in the propagated sound wave as such, but rather by the kinetic sound component, i.e. particle displacement, particle velocity, or particle acceleration (Fig. 1a). Particle acceleration has been pointed out as a likely candidate for the auditory stimulus for the sensory cells (Enger, 1966), and a study by Sand (1974) clearly supports this proposal. In fish without swimbladders, particle motion must be the only possible stimulus parameter. For a fish with a swimbladder, however, sound pressure also can stimulate the sensory cells because the swimbladder can act as a pressure-to-displacement transformer. For the lowest frequencies, however, the swimbladder seems to play no role in sound perception (Sand and Enger, 1973; Sand and Hawkins, 1973).

Physiological studies on infrasound perception

Replotting fish audiograms as acceleration thresholds reveals a threshold curve that is fairly flat in the low frequency range (Fig. 1b). Accordingly, one might expect that the hearing range in fish could extend far down in the infrasound range.

The first report on infrasound perception was published by Sand and Karlsen (1986), who were able to obtain responses as far down as 0.1 Hz in codfish (*Gadus morhua*). Karlsen has obtained similar results from perch (*Perca fluviatilis*) (1992a) and plaice (*Pleuronectes platessa*) (1992b). The methods used have been described in these papers. Sensitivity to sound was tested

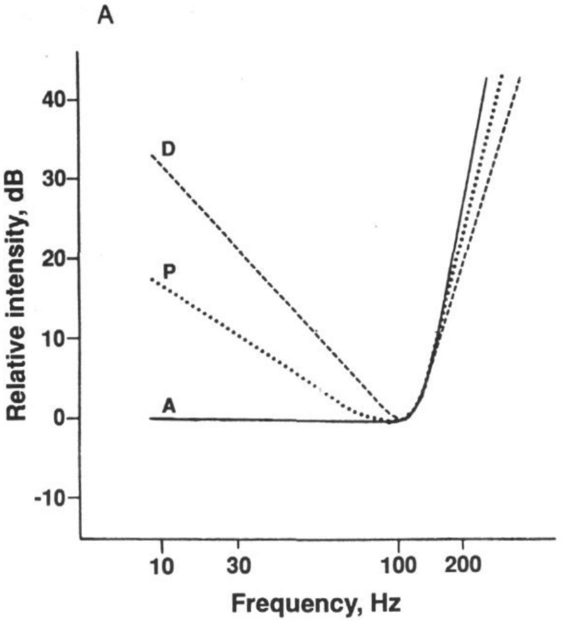

Figure 1. A. Hypothetical fish audiograms related to particle displacement (D), sound pressure (P), or particle acceleration (A). Auditory thresholds have usually been related to particle displacement or sound pressure, leaving the impression that infrasound hearing seems unlikely. By relating thresholds to particle acceleration, the apparent increase in thresholds toward lower frequencies disappears (from Karlsen, 1992c). The relation between particle displacement (d), velocity (v), and acceleration (a) is the following: $v = d(2\pi f)$; $a = d(2\pi f)^2$. Sound pressure is proportional to v.

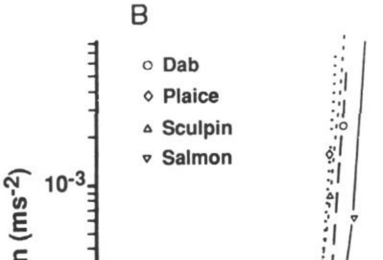

Figure 1. B. Auditory particle acceleration thresholds for four species. Data have been replotted from Chapman and Sand (1974), Hawkins and Johnstone (1978), and Pettersen (1980) (from Karlsen, 1992c).

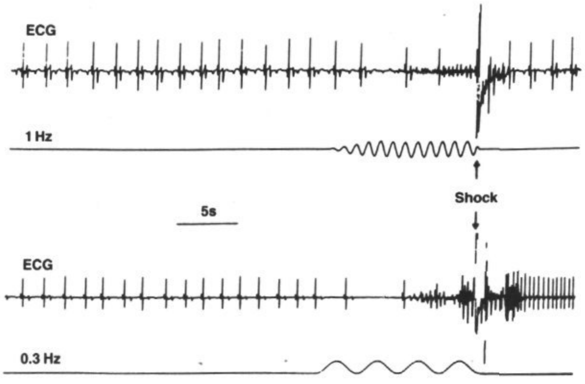

Figure 2. Record of electrocardiogram (ECG) in perch placed in the acoustic tube. A conditioned slowing of the heart rate (bradycardia) is seen in response to 1 Hz and 0.3 Hz infrasound stimulation, shown in the lower trace of each example. An electric shock was given at the end of each stimulus (from Karlsen 1992a).

by a cardiac conditioning technique (Chapman and Hawkins, 1973). An example is shown in Figure 2 for the perch, and the infrasound audiogram for plaice is given in Figure 3. Indirect evidence makes it probable that sole (*Solea solea*) can be included in the list of fish perceiving infrasound (Lagardère and Villotte, 1990).

An important question was whether infrasound reception really is hearing – in the sense that the inner ear is the sensory organ involved – or whether the receptors reside in the lateral line organ. It is now documented that the latter possibility can be ruled out (Karlsen and Sand, 1987; Karlsen, 1992a). The lateral line organ is certainly sensitive to low-frequency oscillatory water

Figure 3. Auditory thresholds for frequencies 0.1–30 Hz in plaice. Points are mean values, vertical bars show one standard deviation. Dotted curve for frequencies 30–300 Hz gives replotted acceleration thresholds for plaice (from Chapman and Sand, 1974) (from Karlsen, 1992b).

motion. The point is that this organ senses hydrodynamic flow or oscillatory movements of the water relative to the fish surface. Such relative water motions are only generated when the sound source is in the immediate vicinity of the fish, i.e. less than a fish length away (Sand, 1981; Enger *et al.*, 1989). At a greater sound source distance, when the fish and surrounding water move in the same way, only the acceleration-detecting inner ear is stimulated.

Hearing thresholds established by the conditioning technique are far below the intensities necessary to alert or to frighten a fish. We have observed changes (bradycardia) in the heart rate in salmon smolts in response to high sound intensities (Knudsen *et al.*, 1992). Such an unconditioned bradycardia can be considered as an alerting response and was obtained for frequencies of 5, 10, 60, and 150 Hz, with a marked increase in threshold with increasing frequency. At 60 Hz, the spontaneous bradycardia or alerting response was obtained at some 50 dB above the hearing threshold established by Hawkins and Johnstone (1978), and at 150 Hz, more than 70 dB above threshold (Fig. 4). Particularly striking was the more pronounced bradycardia (i.e. longer heartbeat interval) occurring during low-frequency stimulation.

Behavioural studies

Among the many studies on the reactions of fish to sound, few deal with infrasound. In most cases the lower limit is 30 Hz, but from some studies one can extract data comprising also part of the infrasound range. Myrberg and co-workers (1976) attracted sharks to a low-frequency sound source. The sound signals were modulated noise bands of 10–20, 20–40, and 40–80 Hz. The two lower noise bands were the most effective in attracting silky sharks (*Carcharinus falciformis*) in the Florida Strait, while the whitetip shark (*C. longimanus*) was attracted equally well to all three noise bands. These tests clearly indicate a sensitivity to low-frequency sound, even in the infrasound range in sharks.

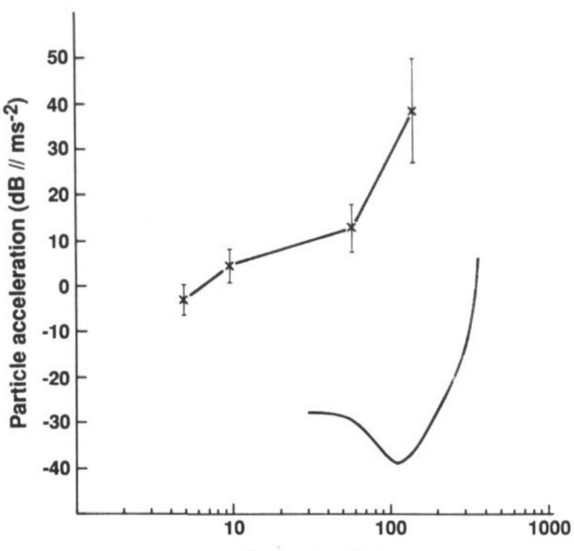

Figure 4. Thresholds for spontaneous changes in heart rate (bradycardia) in juvenile Atlantic salmon, compared with particle acceleration audiogram (lower curve). The audiogram is based on data from Hawkins and Johnstone (1978) for frequencies above 30 Hz (from Knudsen *et al.*, 1992).

Behavioural studies on the reaction to infrasound in bony fishes are scarce. Olsen (1979) reported an avoidance reaction of herring stimulated with noise bands of 50–100 and 3–10 Hz. To our knowledge, this is the earliest report in which an infrasound source has been used.

In fisheries research, there has been great interest in studying the reaction of fish to fishing vessels and fishing gear, particularly in connection with acoustic methods of population assessment (e.g. Olsen, 1979; Olsen *et al.*, 1983; Ona, 1988; Ona and Godø, 1990; Misund, 1990). From observations on cod, haddock, herring, and polar cod, these species all seem to react to a passing vessel, particularly to the propeller noise. The low-frequency components in vessel and gear noise are very strong, extending into the infrasound range. Whether the infrasound components in the noise play any role in the fish's reaction to the trawl is another matter.

In the studies mentioned above, a reaction to low-frequency noise was demonstrated by swimming away from the sound source. However, there are also examples of an attractive effect of low-frequency stimulation. Chapman (1976) found that cod, saithe, and lythe avoided a low-frequency, narrow-band sound source (down to 30 Hz) in experiments performed during one year, whereas they were attracted to the same sound source the following year. Low-frequency, pure-tone stimulation, on the other hand, always attracted fish.

In experiments in which recordings of vessel and trawl sound were played back to cod and herring in a pen, Engås *et al.* (1992) found clear behavioural reactions to the unfiltered sounds and also to filtered sound in the 60–300 Hz range. Filtered noise in the 300–3000 Hz range evoked a strong reaction in herring, but not in cod. The low-frequency band of 20–60 Hz did not evoke a convincing response in either species. Unfortunately, infrasound stimulation was not included in these experiments, but from these results there seems to be no reason to believe that infrasound would be important for fishing operations.

Even if the infrasound component in ship and gear noise is of little or no importance for the orientating ability of the fish, however, we feel convinced that infrasound is important to fish under other circumstances and for other purposes. For example, it has been postulated that infrasound perception may play a role in long-range navigation (Sand and Karlsen, 1986).

There is reason to believe that there are species differences with respect to the possible reaction or response that a fish may show towards an infrasound source. In the following we present observations on salmon during infrasound stimulation.

Behavioural response to infrasound of salmon in a tank

Freely swimming salmon smolts have been observed with a video camera in a 4 × 5 m, 2.5 m deep, concrete basin during sound stimulation. The basin was supplied with an adjustable tarpaulin bottom, making it possible to make a depth gradient of 0.5–1.5 m in the tank. The deepest spot could be positioned at various places with respect to the sound source.

Only two sound frequencies were tested, 10 and 150 Hz. Pure tone 150 Hz was produced by a J9 underwater loudspeaker (lower frequency limit about 30 Hz). The underwater infrasound source consisted of an aluminium tube 1.2 m in length, with a 16 cm piston at one end and an electric motor at the other. By means of eccentric coupling to the motor, the piston was driven back and forth at 10 Hz with a peak-to-peak amplitude of 4 cm (for details, see Knudsen *et al.*, 1992).

A small school of 10–20 fish could be observed swimming placidly around in the basin before the sound was turned on, but at the onset of the 10 Hz sound the reaction was immediate. Fish close to the source showed a flight reaction, swimming away from the source. By analysing videotapes, the critical distance at which the flight response occurred was found to be about 1 m, corresponding to a sound level (measured as particle acceleration) some 10 dB above the level for unconditioned bradycardia. By repeating the stimulation, even up to 20 times over a 3–4 h period, the flight reaction was maintained.

Two groups of salmon were tested in this experiment; one group was caught in the wild a few days before the experiment, the other consisted of farmed fish. An interesting difference between the two could be observed. When the "wild" fish were stimulated with 10 Hz, they immediately escaped to the deepest part of the tank, even if this point was directly under the sound source. The domesticated salmon, on the other hand, swam as far away from the source as possible.

The observations made during 150 Hz stimulation were in striking contrast to the reactions seen in response to the 10 Hz stimulation. No visible reaction to intense 150 Hz stimulation could be observed, even when the fish were only a few centimetres from the loudspeaker membrane.

Observation on salmon smolts in the wild

In the river Sandvikselven near Oslo, we have made some field observations on seaward-migrating salmon smolts. At a particular spot in the river, the water flows in two parallel runs. At the end of one of them, a trap is placed so that the number of smolts passing can be counted. The same two sound sources described above were placed close to the trap. The sound stimulation periods lasted from 10 to 40 min, and were followed by silent periods of the same duration.

Intense sound of 150 Hz had no visible effect on the migrating smolts, as measured by the numbers passing downstream, but the effect of 10 Hz stimulation was dramatic. In nine periods with 10 Hz sound, only 6 salmon passed, compared with 338 salmon passing during nine silent periods of the same duration.

Concluding remarks

Infrasound perception in fish now seems well documented. Among the rather few species for which we have behavioural data, there is a clear distinction between sharks and teleosts. Large sharks are attracted to an infrasound source and will even attack it, whereas the fairly small teleosts investigated are scared by infrasound. The behavioural repertoire may be vastly different in various species. One might easily imagine that the response, i.e. attraction or avoidance, depends on whether the species is a natural predator or prey. It is also possible that small specimens may show a fright reaction, whereas in larger adult fish this may change to attraction. The possible importance of infrasound to fishing operations is as yet uncertain.

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Visual physiology of walleye pollock (*Theragra chalcogramma*) in relation to capture by trawl nets

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Zhang, X. M., and Arimoto, T. 1993. Visual physiology of walleye pollock (*Theragra chalcogramma*) in relation to capture by trawl nets. – ICES mar. Sci. Symp., 196: 113–116.

The visual function of the walleye pollock (*Theragra chalcogramma*) was investigated in relation to how target fish distinguish trawl fishing gear in the capture process. Retinas were sampled from the trawl catch and prepared for histological study. The visual acuity of the retina was examined to determine the scale effect of the minimum separable angle, which can be related to the maximum sighting distance of the visual target under ideal conditions of light intensity and transparency. Furthermore, a model of the escape route of fish during capture by trawl gear is discussed, as is the possible limit of escape distance in relation to the maximum sighting distance. In the case of dark optical conditions at fishing depths of 200~400 m, the weak response of walleye pollock toward the gear could be suggested to be due to lower visual acuity and reduced sensitivity to colour.

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Introduction

The behaviour of fish toward trawl gear has been investigated to clarify the capture process and to establish rational designs for gear, by means of laboratory experiments and field observations summarized by Miyazaki (1965), Inoue (1985) and Wardle (1986).

The recent development of underwater observation techniques during trawl operations has provided a clearer idea of events during the capture process (Wardle, 1983, 1986; Glass and Wardle, 1989). Wardle (1986) suggested that gear avoidance by fish during capture can be predicted from the visual range and swimming speed. In this respect, the reactions of fish to trawls towed in light and dark conditions are discussed by Glass and Wardle (1989). These observations have suggested that vision is the most important sense in the various reactions of fish to approaching gear.

How can fish see the gear? This question can be explained by the following four factors of the visual function: form vision, motor vision, colour vision and photosensitivity of the target fish. A physiological approach can be an appropriate aid to understanding their visual functions such as visual acuity, retinomotor response, flicker fusion frequency, and photosensitivity/spectral sensitivity with the aid of histological and electrophysiological techniques (Ali, 1975; Nicol, 1989; Douglas and Djamgoz, 1990). Behavioural studies can also be helpful in obtaining basic knowledge of fish response toward stationary and moving nets (Blaxter and Parrish, 1965; Parrish, 1969; Cui *et al.*, 1991). Several pioneer studies advanced net avoidance models depending upon differences between fish swimming speeds and towing speed in relation to the scale of gear (Blaxter *et al.*, 1964; Barkley, 1972; Wardle, 1986). According to the wide range of accumulated knowledge on fish behavioural responses, the visual response may be considered to be one of the most important factors, with fish being able to detect an object by contrast discrimination against the background. The visual function of fish is, however, determined by light intensity, which is influenced by the depth and time of day and water transparency.

The present paper describes and discusses the visual acuity of walleye pollock (*Theragra chalcogramma*) in relation to their maximum sighting distance to recognize the gear. The relationship between maximum sighting distance and maximum swimming speed in the trawl capture process is discussed from the viewpoint of possible limits to escape distance.

Materials and methods

To examine the visual function of walleye pollock, retinas were collected from the codend catch immediately after being hauled on board. Fish were taken from a depth of 200~400 m on the east coast of the Kamchatka Peninsula and off the northern island (Hokkaido) of Japan in 1988, 1989, and 1991. By histological examination of the retinas, the minimum separable angle, or visual acuity, was determined from the density of the visual cells (cones) in the retinal region, using maximum density calculated from a formula given by Tamura (1957). The maximum sighting distance of walleye pollock and its scale effect were estimated from the visual acuity. A model of the escape route of fish ahead of a midwater trawl net was also constructed. The possible limit of escape distance was compared with the maximum sighting distance at which gear could be recognized for various target sizes and swimming speeds.

Results

Visual acuity of fish

The morphological acuity is the angle subtended at the nodal point of the eye by two adjacent receptors. Acuity in simple cases depends on both the target size and the density of cones. The change in minimum separable angle was examined using 14 walleye pollock ranging in size from 11 cm to 65 cm as shown in Figure 1. The visual acuity is here defined as the reciprocal of this angle. The results showed an increasing tendency in visual acuity with size of fish, and the minimum separable angle of walleye pollock was stable at approximately 10 min (0.17 degrees) for fish larger than 30 cm. Visual acuity of walleye pollock is assumed to be poorer than that of skipjack tuna (*Euthynnus pelamis*) (2.3 min) and king mackerel (*Scomberomorus cavallai*) (4.2 min) determined by Tamura and Wisby (1963). The retinal structure of walleye pollock showed lower visual acuity and higher photosensitivity when compared with these pelagic migrating species; walleye pollock have about one-tenth of the human visual acuity of 1 min determined by Douglas and Hawryshyn (1990). The higher acuity of larger fish indicates a capability to distinguish a smaller target object, or an object further away, than smaller fish can distinguish.

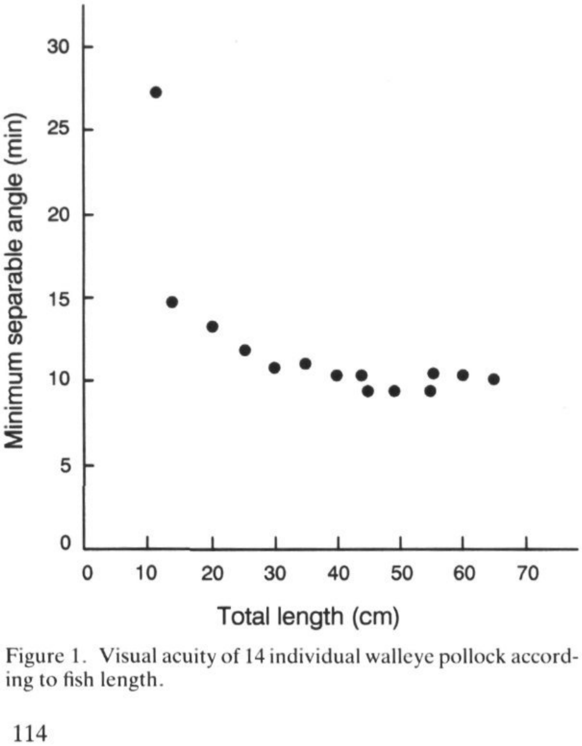

Figure 1. Visual acuity of 14 individual walleye pollock according to fish length.

Maximum sighting distance

The maximum sighting distance of walleye pollock for different sizes of visual target can be estimated from the visual acuity as:

$$D = (l / \alpha)$$

where α is the minimum separable angle in radians, and l the target size. By assuming ideal light and clear water conditions, a target size of 2 cm, for example, gives a maximum sighting distance of 6 m for a fish longer than 30 cm, and 4 m for a 20 cm fish. The maximum sighting distance is also determined by the target size, as shown in Figure 2. The results show that a target size of 4 cm can be recognized from a distance of 13 m by large pollock in ideal optical conditions. In other words, the diameter of a float or rope smaller than 4 cm cannot be clearly distinguished by walleye pollock at a distance exceeding 13 m.

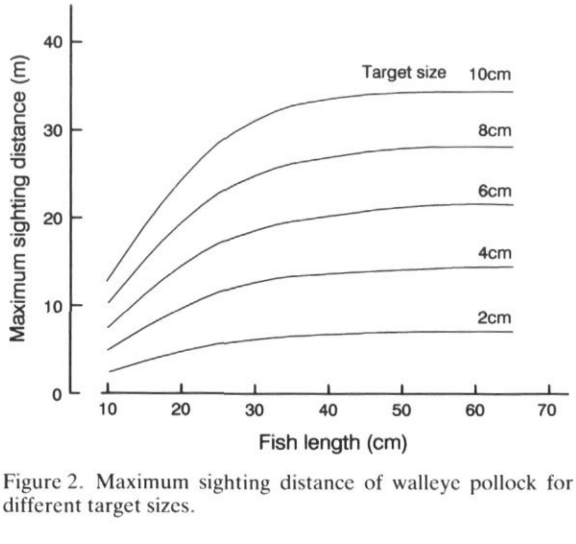

Figure 2. Maximum sighting distance of walleye pollock for different target sizes.

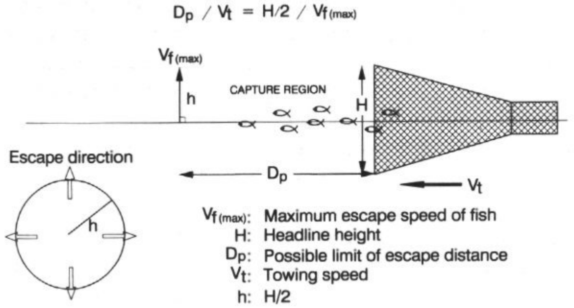

Figure 3. Diagram defining the possible limit of escape distance in the capture process of a midwater trawl net. For explanation see text.

Possible limit of escape distance

A schematic model of the escape route of fish ahead of a midwater trawl net is illustrated in Figure 3. For this purpose, it is assumed that the fish are located in the centre of the frontal area of the net mouth. If fish swim in a direction at an angle of 90° to the towing direction and at maximum swimming speed, the possible limit of escape distance (D_p) can be obtained by the following equation:

$$D_p/V_t = 0.5H/V_f$$

Where V_t is the towing speed, H the headline height, and V_t the maximum swimming speed. During trawling, the possible limit of escape distance of fish to overcome the approaching headline, footline or wings can be considered by using the maximum swimming speed at different temperatures as determined by Arimoto *et al.* (1991). Figure 4 shows the relationship between the maximum sighting distance and the possible limit of escape distance from the midwater trawl. Assuming a headline height of 50 m and towing speed 4 kt, in the case of a rope of diameter 2 cm, the minimum distance for escape is far beyond the maximum sighting distance. When the gear approaches close enough for fish to recognize it, the fish may remain inside the minimum distance and cannot avoid the headline even with the shortest route and maximum speed. But in the case of a 6 cm target size, the larger fish can recognize the gear at 20 m, which may give a sufficient chance of escape reaction at temperatures of 2~10°C. The higher swimming activity at higher temperatures indicates an increasing likelihood of escape owing to the elevation of swimming capability. To successfully avoid the gear, the fish is required to start its escape reaction at a distance of 20 m ahead of the trawl net in water of 2°C, but the possible limit of escape distance can be reduced to 14 m when the temperature is 10°C owing to the higher maximum speed achieved by the fish at higher temperatures.

Figure 4. Relationship between the maximum sighting distance (solid curves) and the possible limit of escape distance (dotted curves) according to target size and water temperature (towing speed 4 kt; headline height 50 m).

Discussion

How a fish recognizes a trawling gear should be the first step in understanding the capture process. The visual function of fish is known to differ among species and is also influenced by the optical condition of their habitat. In this report, the visual acuity of walleye pollock was examined by histological observations on the density of visual cells (cones). This information leads to the concept of maximum sighting distance, then a limit of possible escape distance using information on the maximum swimming speed of fish. It should be noted that the maximum sighting distance is predicted from the relationship between the visual cell density and the visual angle at which the fish can just distinguish two points (such as meshes or knots) as separate targets. However, acuity can also be expressed as line acuity and grating resolution (Schwassmann, 1975; Miyazaki and Nakamura, 1990), which tend to be larger than visual acuity. In the capture process, the trawl gear presents complex multiple visual stimuli, so that line acuity may be considered to be a most important factor in the visual range of gear such as ropes or net twines which present line targets. The shape of the target also influences the visual range for response (Kawamura and Shimowada, 1983; Douglas and Hawryshyn, 1990). From these points of view, it can be suggested that fish may have larger visual ranges for a trawl net than the maximum sighting distance derived from the visual acuity. Further work is required, especially to quantify the characteristics of these complex visual stimuli and to observe fish responses in different parts of the gear.

Visual acuity is known to be greatly influenced by light intensity. In addition, the visual range can be determined by the contrast of the target. Anthony (1981) reported a reduction of reaction distance with reduced contrast. The most important factor of gear as the visual cue, then, may be the whole image with its contrast against the background. Fish may detect the overall image of approaching trawl gear even if the details of ropes and meshes cannot be recognized beyond the maximum sighting distance. Besides, the vision of marine fish has been found particularly well adapted to detecting very small differences in contrast. In very clear water, the visual range of fish can be considered to be longer than the maximum sighting distance for the isolated components of the gear as larger parts of the gear are seen as collections of components.

Concerning the visual function of fish, one of the determining factors is the retinomotor response. That is the alternation between the light-adapted state (photopic vision) and the dark-adapted state (scotopic vision) which can be defined by depth and time of day. Jerlov (1976) indicated that below 100 m depth, the wavelength becomes a narrow spectral range of mostly blue light. The intensity of the light is also rapidly reduced with depth. In the case of trawling on the North Pacific fishing ground at 200~400 m depth, this means that light levels are extremely low. In this dark environment with a dim monochromatic background, the scotopic or the mesopic vision state may give a higher photosensitivity but with lower acuity and less capability for colour and motor vision, as summarized by Blaxter (1980). The visual function of walleye pollock in these conditions is considered too weak to recognize the approach of a trawl net as a visual cue, especially at night.

Wardle (1986) emphasized the importance of knowledge about the visual range and swimming capability as parameters in the trawl capture process. The swimming performance of fish depends on fish length and water temperature, so that the possibility of net avoidance is greatly influenced by these two factors. In this report, the possible limit of escape distance has been obtained from an evasion model, and was considered to be the determining factor in comparison with the maximum sighting distance. The fish cannot avoid the approaching gear when the possible limit of escape distance is beyond the maximum sighting distance. Further investigation into the visual function and response of fish toward trawl gear is required, to establish higher efficiency and selectivity in size and species, in relation to the swimming capability of fish.

Acknowledgements

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ICES mar. Sci. Symp., 196: 117–121. 1993

The measurement of muscle fatigue in walleye pollock (*Theragra chalcogramma*) captured by trawl

Gang Xu, Takafumi Arimoto, and Yoshihiro Inoue

Xu, G., Arimoto, T., and Inoue, Y. 1993. The measurement of muscle fatigue in walleye pollock (*Theragra chalcogramma*) captured by trawl. – ICES mar. Sci. Symp., 196: 117–121.

Walleye pollock (*Theragra chalcogramma*) were captured by otter trawl in the fishing grounds off Hokkaido, northern Japan. In order to investigate the muscle fatigue of a fish in relation to its swimming ability during the capture process, samples of the dorsal white muscle of captured fish with a mean fork length of 43 cm were taken on board and the concentrations of lactic acid and ATP-related compounds (ADP, AMP, IMP) were later determined in the laboratory. Lactic acid concentration ranged from 52 to 239 mg 100 g^{-1} wet muscle and ATP concentration from 0.13 to 1.57 μmol g^{-1} wet muscle in the fish immediately after capture. Some of the fish had a higher ATP concentration of about 1 μmol g^{-1} with a lower lactic acid concentration of about 50 mg 100 g^{-1}, very similar to that observed in the fish after 24 h recovery in a 500 litre holding tank. During a recovery period of 24 h, the ATP concentration did not increase, but the concentration of ATP-related compounds such as ADP and AMP increased gradually. The results suggest that some of the walleye pollock might not have experienced complete muscle fatigue, and might be able to swim longer inside the net, which was towed at speeds of 4.0 to 4.6 knots.

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Introduction

Changes in carbohydrate metabolism in fish following severe muscular exercise have been well reported in relation to muscle fatigue (Beamish, 1966a, 1968; Pritchard *et al.*, 1971; Johnston and Goldspink, 1973; Driedzic and Hochachka, 1976). In most fishes, the lateral musculature consists of two main fibre types, usually termed red and white muscle. The red muscle is aerobically active by itself during swimming at sustained speeds, whereas during burst swimming the white muscle becomes active together with the red muscle. The white muscle carries out anaerobic glycolytic metabolism which results in glycogen depletion and lactic acid accumulation (Bone, 1966). The glycogen in white muscle is one of the major fuel sources supplying the energy required during swimming. In the glycolytic pathways, the formation of ATP, which serves as the immediate source of energy for muscle contraction, is the most important function. In view of the relationship between energy supply and muscle contraction, studies on the concentrations of muscle lactic acid and ATP-related compounds may improve the understanding of muscle fatigue in fish after strenuous exercise, such as swimming inside towed fishing gears. Much of the older literature in this area has been reviewed by Driedzic and Hochachka (1978).

Walleye pollock (*Theragra chalcogramma*) are frequently captured by otter trawls in the offshore fishery of northern Japan. Observations with an underwater video camera during the capture process have shown that most of the fish were inactive, both in the net mouth and inside the net, which was towed at about 3.8 knots (Inoue *et al.*, 1992). However, from the video recordings, it could not be determined whether the fish had been exhausted by swimming along with the trawl at the towing speed. In this study, a series of experiments were carried out to determine the level of muscle fatigue in captured walleye pollock.

Material and methods

All research tows were made by two 124 G.R.T. type commercial trawlers RV "No. 85 Yawata-maru" during 27–28 July 1988 and RV "No. 67 Eishou-maru" during 24–25 July 1989, in the fishing ground off Kushiro on the east coast of Hokkaido, Japan. The gear was towed along depth contours ranging from 154 to 235 m. The towing speed varied between 3.8 and 4.6 knots according to sea conditions. The towing duration was between 50 and 180 min, depending on the number of fish inside or around the net. Samples of walleye pollock were taken at random about 2 min after the net was hauled aboard at the end of each tow. In the 1988 trials, muscle samples were taken from the fish immediately after capture. In the 1989 trials, the fish were first sampled from the catch immediately after capture and then placed in an aerated 500 litre holding tank for recovery. Muscle samples were then taken from the fish after recovery periods of 0.3, 6, and 24 h (Table 1).

For analysis of both lactic acid and ATP-related compounds, muscle samples (1 g) were cut from the dorsal white muscle block above the anus of freshly killed fish. The muscle pieces were then placed in a scintillation vial with 5 ml of cold (0°C) perchloric acid (PCA) solution (6%) to remove protein. After the muscle pieces were homogenized in ice, the samples were kept in a "Styrofoam" bag containing dry ice and brought back to Tokyo University of Fisheries for biochemical analyses. The mixture was filtered with a 0.45 μm syringe filter and the filtrate was centrifuged at 3000 g for 8 min. The supernatant solution was stored at -30°C until analysis. Lactic acid concentration was determined colorimetrically by the method of Barker and Summerson (1941). All readings were made at 560 nm in a spectrophotometer (Hitachi, UV-1000). Lactic acid concentration is expressed as milligrams of lactic acid per 100 g wet muscle.

ATP and its related compounds, ADP, AMP, and IMP, were determined by high-performance liquid chromatography (HPLC), measuring UV absorption at 254 nm (Suwetja *et al.*, 1989). A 5 μl PCA extract was injected into a TSKgel ODS-80™ column (5 μm, 4.6 × 150 mm, Tosoh) equilibrated with 3% methanol in 0.05M K_2HPO_4 buffer, pH 6.5 (PB). Elution was conducted at a flow rate of 0.5 ml min^{-1}, first with a linear gradient between 3% and 15% methanol in PB for 30 s, then with 15% methanol in PB for 19.5 min. Identification of ATP-related compounds was carried out by comparing the retention time of peaks in HPLC between the sample and standard compounds. ATP concentration is expressed as micromoles ATP per 1 g wet muscle, as are the ADP, AMP, and IMP concentrations. All changes in lactic acid and ATP-related compounds were tested for significance using Student's t test.

Results

In the 1988 trial, sampling was carried out over a total of five tows. Six to eight individuals were sampled for each tow. For the fish immediately after capture, the concentration levels of muscle lactic acid varied between 52 and 239 mg 100 g^{-1}. From a total of 38 samples, 14 samples had lactic acid concentrations that were under 100 mg 100 g^{-1}. On the other hand, muscle ATP concentrations in the fish immediately after capture were relatively low. With the exception of a few samples, most were under the level of 1 μmol g^{-1} (Fig. 1). The mean values of lactic acid and ATP concentrations for samples in each tow are given in Table 2. Most of the fish immediately after capture were characterized by a high lactic acid and low ATP concentration in their white muscles. However, some fish had a low lactic acid and high ATP concentration. These conflicting results between individuals and tows may be associated with differences in operating conditions, or variations in fish exertion during the capture process. However, we found no conclusive evidence to explain the relationships quantitatively.

In 1989, measurements were carried out in fish after different recovery periods. Fish were removed from the holding tank and decapitated immediately. The mean value of lactic acid concentration for five individuals after 18 min recovery was 154.2 mg 100 g^{-1}. This value

Table 1. Operating conditions of the fishing boats during the sea trials collecting the samples of walleye pollock for biochemical analyses.

Tow no.	Sample date	Towing period (min)	Towing depth (m)	Towing speed (kt)	Fishing method
1	27 Jul 1988	130	163~215	4.6	Bottom trawl
2	27 Jul 1988	50	205~235	4.0	Mid-water trawl
3	27 Jul 1988	180	195	4.2	Bottom trawl
4	27 Jul 1988	125	190	4.5	Bottom trawl
5	27 Jul 1988	125	185	4.1	Bottom trawl
6	24 Jul 1989	135	205	3.8	Bottom trawl
7	25 Jul 1989	85	165	4.5	Bottom trawl
8	25 Jul 1989	78	154	4.3	Bottom trawl

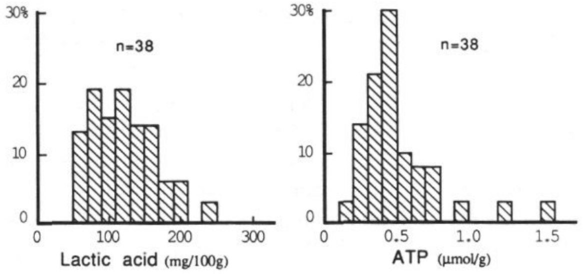

Figure 1. Percent frequency distributions of concentrations of muscle lactic acid and ATP in walleye pollock immediately after capture in tows 1 to 5 (see Table 1).

was higher than that for the fish immediately after capture (121.7 mg 100 g^{-1}). After 6 h recovery, the lactic acid concentration had not changed significantly ($P>0.05$), compared with that in the fish after 18 min recovery. By contrast, the fish after 24 h recovery showed a great reduction in lactic acid concentration (Fig. 2). This mean value was 52.6 mg 100 g^{-1}, very close to that in some fish with low lactic acid.

ATP concentration remained low and unchanged during all recovery periods (Fig. 2). In addition to lactic acid and ATP, measurements of ADP, AMP, and IMP were also carried out to observe the total change in the free adenylate pool. The concentrations of both ADP and AMP in muscle increased, whereas IMP decreased as the recovery period increased. The total free adenylate pool [(ATP) + (ADP) + (AMP)] increased gradually during the recovery process. After 24 h recovery, the total free adenylate pool was restored to 12.15 μmol g^{-1}, which was three times as much as that after 18 min recovery. The energy charge, [(ATP) +0.5(ADP)]/[(ATP) + (ADP) + (AMP)] as defined by Atkinson (1968), was low at about 0.20 in all states of recovery (Table 3).

Discussion

Many investigators have used lactic acid as a measure of muscle fatigue in fish following exercise (Beamish, 1966a). For Atlantic cod (*Gadus morhua*) of about 40 cm length, white muscle lactic acid in the fish after swimming at 130 cm s^{-1} for 30 min was higher (189 mg 100 g^{-1}) than that in unexercised fish (66.8 mg 100 g^{-1}). Despite 4 h recovery, its lactic acid level was almost unchanged and remained high (153.7 mg 100 g^{-1}). After 8 h recovery, the muscle lactic acid disappeared gradually to near unexercised levels (52.9 mg 100 g^{-1}) (Beamish, 1968). With reference to lactic acid concentration in plaice *Pleuronectes platessa* L. immediately after capture by otter trawl, a high level of 297–396 mg 100 g^{-1} in white muscle was observed (Wardle, 1978). That muscle lactic acid in walleye pollock immediately after capture was much higher than after 24 h recovery is in accord with the observations of Beamish (1968) and Wardle (1978). Based on absolute lactic acid values, it seems likely that most of the walleye pollock captured by otter trawl have experienced strenuous muscular exer-

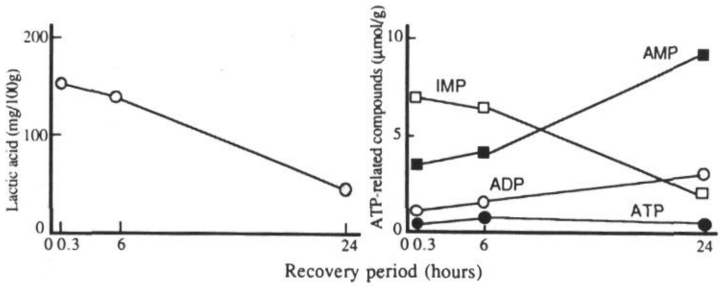

Figure 2. Changes in muscle lactic acid and ATP-related compounds in walleye pollock after different recovery periods. Values shown are means for five individuals (see text).

Table 2. Mean values for muscle lactic acid and ATP-related compounds of walleye pollock immediately after capture by trawls.

Tow no.	No. of fish	Fork length (cm)	Lactic acid (mg/100 g)	ATP (μmol/g)
1	6	41.7±4.1[a]	82.2±16.0	0.98±0.33
2	8	45.1±4.5	140.3±19.6	0.41±0.11
3	8	40.0±4.8	156.3±37.9	0.52±0.12
4	8	41.8±6.1	104.8±36.2	0.41±0.11
5	8	43.9±5.4	115.3±52.7	0.34±0.11
Mean		42.5±5.4	121.7±43.9	0.51±0.27

[a] Standard errors (s.e.).

Table 3. Comparisons of the values of total free adenylate pool and energy charge after different recovery periods in walleye pollock.

Metabolite	No. of fish	Recovery period (h)		
		0.3	6	24
Adenylate pool (μmol/g)[a]	5~7	4.74±0.63[c]	5.79±0.58	12.15±1.26
Energy charge[b]	5~7	0.17±0.01	0.21±0.01	0.16±0.02

[a] (ATP) + (ADP) + (AMP).

[b] [(ATP) +0.5(ADP)]/[(ATP) + (ADP) + (AMP)].

[c] Standard errors (s.e.).

tion and become fatigued during the capture process. However, in some of the walleye pollock, only lower lactic acid levels, corresponding to that after 24 h recovery, were detected. These fish are likely to have a different level of muscle fatigue from that in most of the fish caught by trawls.

With respect to changes in nucleotides, Jones and Murray (1957) reported that in rested cod *Gadus callarias*, ATP concentration in muscle was 5.34 μmol g^{-1}, and in exhausted cod which were caught by trawl, ATP decreased to a low level of 0.26 μmol g^{-1}, with a striking increase in IMP. Usually the rate of utilization of ATP for muscle action is related to its rate of production through glycolytic metabolism. As the work load of the tissue exceeds its aerobic capabilities, the 5′-AMP deaminase converts AMP to IMP, and the adenylate pool is decreased, resulting in muscle ATP reduction (Driedzic and Hochachka, 1978). Our observations in fish immediately after capture showed that ATP concentrations in white muscle were low for most of the fish. In contrast to the gradual disappearance of muscle lactic acid following recovery, muscle ATP was not restored significantly in any recovery period ($P>0.05$) (Fig. 2). However, the obvious increase in the total free adenylate pool after recovery might account for some of the muscular recovery from fatigue (Table 3). The changes in the free adenylate pool were very similar to the patterns between rested and exhausted fish observed by Jones and Murray (1957) and Driedzic and Hochachka (1978). On the other hand, the level of energy charge was almost unchanged and remained low during recovery periods. This fact may indicate that these fish had not completely returned to an unexercised state even after 24 h recovery. It seems likely that slow muscular recovery from fatigue might be associated with degree of fatigue, as well as experimental conditions including influences of engine noise and vessel vibration.

In the present study, the capture of walleye pollock could have occurred at any time during the tow. It is hard to assign qualitative figures to strength of exercise and physical condition of fish (Beamish, 1966a). When fish are able to detect trawl gears visually, they have been observed to maintain station with the gear as it is towed. When fish are unable to swim to keep up with the trawl, they become exhausted and drop back into the codend (Wardle, 1983). However, in the absence of vision, fish can only react to a moving net by a startle reaction when struck by the net (Glass and Wardle, 1989). Since our trawls were towed in the deep sea at about 200 m, the fish were estimated to recognize the trawl gear probably with a low acuity in this dark environment (Zhang and Arimoto, 1993). During the capture process video recordings were taken to observe the behaviour of walleye pollock at a water temperature of 2°C, while artificial light was provided by a halogen lamp of 150 W. The video recordings showed that most of the walleye pollock inside the net did not swim actively and drifted passively towards the codend, even in the artificial light condition (Inoue *et al.*, 1992). For Gadidae of similar size, it was found that at low temperatures from 0 to 5°C, Atlantic cod could only maintain endurance swimming for several seconds at high speeds of above 2 m s^{-1} (Beamish, 1966b; He, 1991). For walleye pollock of 50–53 cm length, the maximum swimming speed estimated from muscle contraction at 5°C was 2.1 m s^{-1} (Arimoto *et al.*, 1991). Here, if the walleye pollock swim to keep up with the trawl at towing speeds of 4.0 to 4.6 knots (2.1 to 2.4 m s^{-1}), the fish would be exhausted to a great extent after burst swimming for a short time. Wardle (1983) suggested that the fish in the codend are exhausted to varying degrees by their efforts made during the capture process. Therefore, some captured walleye pollock with a lower lactic acid and higher ATP concentration probably had not experienced complete muscle fatigue during the capture process and could have swum for longer. This result implies that inactive fish observed with an underwater video camera might not have swum long with the trawl at high speeds, and before becoming completely exhausted most of them already dropped into and struggled in the codend, while some were quiet in the codend.

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Survival of gadoids that escape from a demersal trawl

Aud Vold Soldal, Arill Engås, and Bjørnar Isaksen

Soldal, A. V., Engås, A., and Isaksen, B. 1993. Survival of gadoids that escape from a demersal trawl. – ICES mar. Sci. Symp., 196: 122–127.

The vulnerability of gadoid fish (saithe (*Pollachius virens* L.), cod (*Gadus morhua* L.), and haddock (*Melanogrammus aeglefinus* L.)) to gear damage was studied in both small-scale and full-scale experiments. Simulated net injuries were inflicted on net-penned saithe and on cod and haddock kept in tanks. The cod and haddock were also physically exhausted by swimming in a treadmill. No immediate mortality was observed for cod and saithe, whereas about 10% mortality was found for haddock. Both saithe and haddock developed infections in the wounded skin areas, leading to a delayed mortality of about 10%. Full-scale field experiments during bottom trawling for cod and haddock in the Barents Sea supported the low mortality rates found in the small-scale tests. No mortality was observed for cod, while for haddock it was less than 10%. The reliability of the results and the implications for fisheries management are discussed.

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Introduction

Whether fish that escape from a trawl codend survive has been a question of concern in recent years. As the abundance and thus the catch per unit effort of many of our economically important fish stocks have decreased, at least partially because of over-exploitation, the authorities and fishermen have become more aware of the importance of conserving undersized fish to improve recruitment to the fishery. In the late 1980s reports indicated high mortality rates among fish (primarily haddock) that had been caught by a trawl but escaped through the codend meshes (Main and Sangster, 1988; Zaferman and Serebrov, 1989). It was even claimed that mesh selection, which for decades has been the basic method for saving small fish, was not worth while as fish escaping from the trawl through the codend meshes would die in any case (Zaferman and Serebrov, 1989).

Subsequently, survival studies of fish escaping from fishing gear were also carried out in Norway. Two small-scale experiments, one with saithe (*Pollachius virens* L.) in net-pens (Soldal *et al.*, 1989) and one with cod (*Gadus morhua* L.) and haddock (*Melanogrammus aeglefinus* L.) in indoor tanks (Engås *et al.*, 1990), were carried out to investigate experimentally the sensitivity of these species towards the kinds of injuries that may rise from contact with gear. In addition, a field experiment was carried out in the course of which fish that escaped through the codend meshes of a commercial bottom trawl were collected and observed for mortality (Soldal *et al.*, 1991). This paper reviews the results of the Norwegian experiments on demersal gadoid fish species.

Materials and methods

Experiment with net-penned saithe

Four groups of saithe ranging in length from 30 to 60 cm were held in net-pens (6 × 6 × 6 m) floating on the sea surface: (1) control (73 fish); (2) anaesthetized control (69 fish): fish were anaesthetized with metomidate on day 0 and not subjected to further treatment; (3) net damage (119 fish): fish were forced to swim through the meshes of a trawl net to simulate escapement through a trawl codend; and (4) induced damage (51 fish): scales and mucus were removed from the body surface (Fig. 1) of anaesthetized fish to simulate gear injuries to the surface of the skin.

Blood samples were taken by heart puncture of four fish from each experimental group 2, 4, 12, and 24 h and thereafter 2, 3, 4, 6, 8, and 14 days after treatment. Haematocrit, Cl^-, K^+ and Mg^{2+} content were

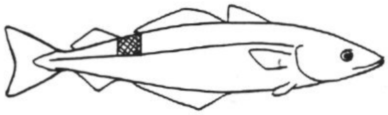

Figure 1. Defined skin injuries of saithe in the induced-damage group. Scales and mucus were removed from the marked skin area using the blunt edge of a scalpel.

measured to identify possible osmotic disturbances caused by loss of scales and mucus. The fish were also examined for external injuries, and dead fish were counted daily.

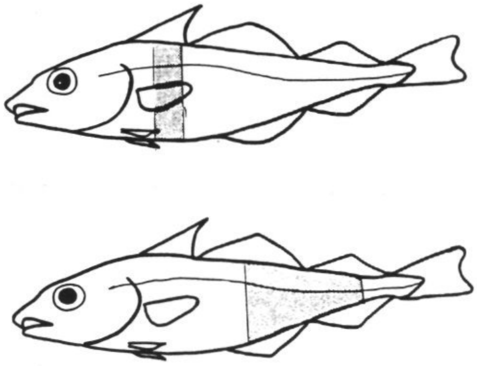

Figure 2. Defined skin injuries of haddock and cod in the tank experiment. Scales and mucus were removed from the marked skin areas using the blunt edge of a scalpel. The upper fish was injured at the maximum circumference of the body, where fish struggling through a net mesh are most likely to be hurt. The lower fish was injured at the tail, where it is likely to be hurt when the tail beats against the net wall of a trawl.

Tank experiment with cod and haddock

This experiment attempted to simulate the combined effect on fish survival rate of exhaustion and skin damage (scale and mucus loss) caused by trawling and escape. Eighty cod (35 to 40 cm) and 35 haddock (35 to 50 cm) were divided into four experimental groups, all kept in indoor seawater tanks (approx. 9 m^2): (1) control (20 cod, 8 haddock); (2) muscular exhaustion (20 cod, 8 haddock): fish were forced to swim in a treadmill with water flowing at speeds increasing from 1.35 to 2 $m\ s^{-1}$, to simulate the swimming activity performed in the trawl mouth and belly; (3) combined muscular exhaustion and net injuries (20 cod, 10 haddock): treated as group (2), but in addition forced to swim through the meshes of a net panel (100 and 110 mm stretched mesh), to simulate escapement from a trawl codend; and (4) combined muscular exhaustion and induced skin damage (16 cod, 8 haddock): treated as group (2), but in addition scales and mucus were removed from predetermined regions of the body surface (Fig. 2) to simulate scale loss during the escapement process. Half the fish were wounded at the maximum circumference of the body, where fish are most likely to get hurt when wriggling through the net meshes. The other half were wounded at the tail, where scales may be lost when the tail is beaten against the net walls of the trawl during swimming movements. After treatment the fish were kept for observation in the tanks for four weeks, and dead fish were counted daily.

Field trials

These investigations were carried out on board a commercial stern trawler off the coast of Finnmark, northern

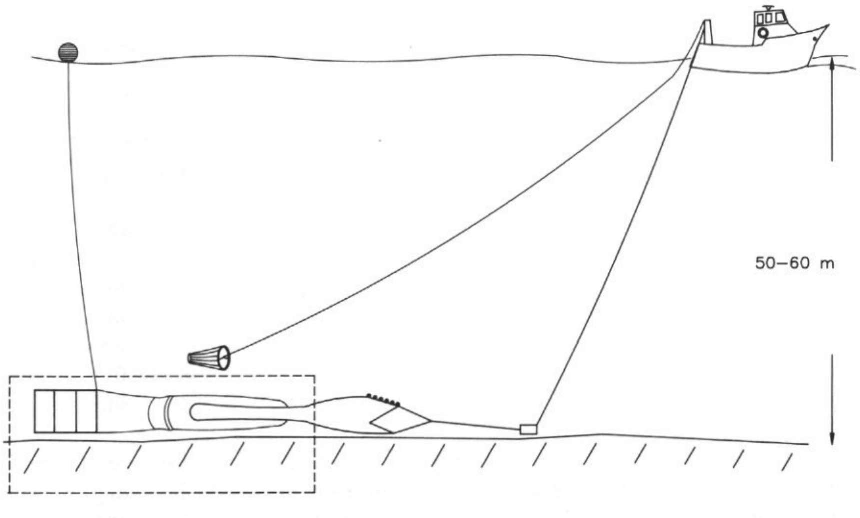

Figure 3. Experimental set-up during trawling with the Cotesi no. 3 demersal trawl. The codend is covered by a small-meshed cover net. The trawling procedure is inspected via the towed ROV "Ocean Rover". The dashed box is enlarged in Figure 4.

Norway, in August 1991, at bottom depths from 30 to 60 m, and at towing speeds of from 3.6 to 3.8 knots. Escaped fish were retained in large net cages (2 × 2 × 5 m) attached to a small-meshed net covering the codend (135 mm diamond mesh, L_{50} of about 45 to 50 cm (Isaksen *et al.*, 1989)) of a Cotesi no. 3 bottom trawl (Figs. 3 and 4). The trawl with the codend cover and the cage mounted was observed with the towed vehicle "Ocean Rover" during selected hauls to ensure that the gear performed as close to normal as possible. Three experimental groups were set up: (1) mesh selection group: a normal (135 mm) diamond mesh codend was used; (2) grid selection group: a metal grid sorting device (55 mm between ribs) was mounted in the front part of the codend; and (3) control group: the cage was attached directly to the trawl belly and no codend was used. Only 10 min towing time was used owing to high fish density in the area. The number of fish, mainly cod and haddock, caught in the cages varied between 150 and 1000. The fish mainly ranged between 20 and 50 cm in length.

Before retrieval of the trawl, the cages were released from the trawl at the seabed by means of an acoustic releaser, and slowly (speed: 1 knot) towed into sheltered waters (20 m bottom depth) where they were anchored side by side to minimize differences in environmental conditions between cages during the observation period. There were three replicate cages of each experimental group, all taken within a period of one week. The fish were not fed during the experiments. The cages were observed for 12 to 16 days by an underwater camera mounted on a small remotely operated vehicle (ROV). Dead fish were counted daily. Sea temperature was stable at about 9°C throughout the observation period. One of the cages in the mesh selection group had to be deleted from further analyses owing to technical problems with the ROV towards the end of the observation period. Differences in mortality between experimental groups were tested by analysis of variance.

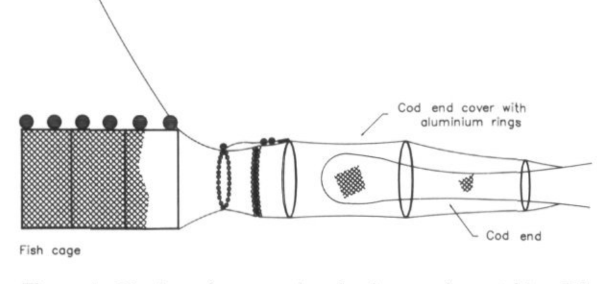

Figure 4. Rigging of cage and codend cover for catching fish escaping through the codend meshes (135 mm).

Results

Small-scale experiments

Saithe survived the first days after treatment in the net pen experiment (Table 1). The haematocrit value and the Cl^-, K^+ and Mg^{2+} content of the blood serum from fish with skin wounds were not significantly different from those of the control group or the anaesthetized control group. This means that the fish showed no signs of osmotic imbalance owing to scale and mucus loss. After 4–5 days, secondary infections appeared in the injured skin areas, followed by an increased mortality rate.

Cod proved to be resistant to scale loss and skin injuries. In the tank experiment one cod (combined muscular exhaustion and induced skin injuries) died after one week, as a result of infection in the wounded skin areas (Table 2).

Haddock were more vulnerable to gear damage than cod and saithe. In the tank experiment, a 10–20% mortality among haddock treated with combined muscular exhaustion and induced skin damage was noted (Table 2). However, the number of haddock in the treatment groups was low, and accordingly we suspect that the accuracy of the estimated mortality rates may be low.

Field experiments

The results of the small-scale experiments agreed well with the field experiments. No mortality was observed for cod. Mortality rates of caged haddock from the mesh selection and grid selection groups varied between 1 and 10% (Table 3). Death occurred within the first five days of captivity. Although the difference between the groups was not significant ($p = 0.1$), mortality in the control group was higher (9 to 32%) than in the selection groups. This was mainly due to predation: the control cages contained a mixture of fish in several size groups, including a number of large cod (>50 cm) that fed heavily on small haddock. However, the exact reason for mortality is not easy to assess. The fish were not fed during the experiments, but gadoids easily endure two weeks without feeding at the low water temperatures (9°C) found in the Barents Sea. Hunger would lead to an increasing mortality throughout the experimental period, in contrast to our findings of mortality in the first few days after capture.

Discussion

Although earlier Scottish reports indicated high mortality (more than 80%) of haddock after escapement from a demersal trawl (Main and Sangster, 1988), and Soviet scientists (Zaferman and Serebrov, 1989) observed considerable amounts of dead cod and haddock on the seabed along the trawl path immediately after a

Table 1. Estimated daily mortality of saithe in the net-pen experiment. The number of fish alive is gradually reduced because fish were sacrificed for blood serum analyses.

Day	Control			Induced damage			Anaesthetized control			Net damage		
	No. alive	No. dead	% daily mortality	No. alive	No. dead	% daily mortality	No. alive	No. dead	% daily mortality	No. alive	No. dead	% daily mortality
0	73	0	0	51	0	0	69	0	0	119	0	0
1	61	0	0	39	0	0	57	0	0	116	1	1.0
2	57	0	0	35	0	0	53	0	0	102	0	0
3	53	0	0	31	0	0	49	0	0	98	0	0
4	49	0	0	27	0	0	45	0	0	93	1	1.0
6	42	3	3.3	22	1	2.1	41	0	0	90	0	0
8	38	0	0	17	1	2.7	36	1	1.3	86	0	0
14	34	0	0	8	5	6.4	29	3	1.6	82	0	0

haul, our small- and full-scale experiments do not support these findings (Soldal *et al.*, 1989; Engås *et al.*, 1990; Soldal *et al.*, 1991).

The survival rate of cod with simulated gear injuries (skin lesions alone or combined with physical exhaustion) in tank experiments, and those fish collected after escaping from a codend during trawling, was nearly 100%. The survival of haddock in both small- and full-scale experiments was also higher than expected from the Scottish and Soviet reports. The low mortality rates for haddock and cod agree with those reported by Main and Sangster (1991) in their latest work. The experiment in net-pens indicates that saithe also may survive escapement well. Similar results were obtained in a recent field experiment carried out in the Faroe Islands (Jacobsen *et al.*, 1992). The mortality attributable to secondary infections observed in the net-pen experiments is probably increased by the high risk of cross-infection in captivity (Holm *et al.*, 1980).

Accurate mortality rates of fish that die of injuries caused by escapement from the codend are difficult to assess. There is no single reason for fish dying. Fish are physically injured not only while passing through the codend meshes, but also by rubbing against the net wall, other fish, and crustaceans within the trawl prior to escapement. Scale loss analyses of cod and haddock withheld in cages after escapement through the codend meshes showed that small fish were more heavily injured than fish in the retention range (45 to 50 cm), which have to struggle to escape (Soldal *et al.*, 1991). This indicates that other factors than the escapement process alone harm fish during trawling. Our method of counting dead fish by underwater camera did not allow us to measure the fish length to investigate a possible length dependency in mortality rates. Skin injuries may lead to instantaneous mortality, mortality within a couple of days owing to osmotic disturbances (Roald, 1980; Rosseland *et al.*, 1982), or to mortality through secondary infections (Holm *et al.*, 1980). In addition, physical exhaustion may increase mortality rates (Beamish, 1966).

Although the level of injuries of fish in the small-scale experiments corresponded well with those observed in field studies (Soldal *et al.*, 1991), the mortality rates found in these experiments cannot be transferred uncritically to field situations. In the full-scale studies, the capturing, handling, and caging of the escaped fish undoubtedly led to unintentional physical damage and stress in addition to that caused by herding, catching and escapement from the trawl. Use of underwater cameras outside and inside the cages during the different stages of the trawling, release, towing and anchoring phases of the experimental procedure revealed several methodological problems that added to the gear-induced mortality. Fish, in particular the smallest, became exhausted and rested against the rear wall of the net during towing of the cages. This increased the scale loss and skin damage. Furthermore, in some hauls considerable num-

Table 2. Mortality (number of fish) in the different treatment groups of the tank experiment.

Treatment	Species	Number	Mortality
Muscular exhaustion	Cod	20	0
	Haddock	8	0
Combined muscular exhaustion and induced skin damage	Cod	16	1 (day 8)
	Haddock	8	1 (day 0)
Combined muscular exhaustion and net injuries	Cod	20	0
	Haddock	10	2 (day 0, day 7)
Control	Cod	20	0
	Haddock	8	0

Table 3. Total mortality of haddock in the individual cages during the field experiment.

Experimental group	Cage no.	Observ. period (days)	No. of haddock	No. of deaths	% mortality	Average mortality (%)
Mesh selection	1	16	340	22	6.5	
	2	15	116	1	0.9	3.7
	3	9	984	*	0	
Grid sorting	1	14	505	27	5.4	
	2	13	114	9	7.9	7.9
	3	13	428	45	10.5	
Control	1	15	127	41	32.2	
	2	14	131	26	19.8	20.3
	3	12	146	13	8.9	

*Cage excluded owing to technical problems with ROV during observation period.

bers of fish were trapped in the funnel between the cage and the trawl during release of the cages. An unknown fraction of the observed mortality of haddock may be ascribed to these experimental faults. The mortality rates of Table 3, therefore, are maximum figures, and do not reflect the mortality caused by gear contact alone.

The control groups in this experiment are not true controls. The fish endured the same trawl capturing process as the experimental groups, with the only difference that they did not pass through a sorting grid or codend meshes to escape. In addition, the control fish were not size selected, and predation added to mortality. The control groups therefore do not add much information to the experiment. The lack of true control fish is a major disadvantage of our experiment.

In spite of the many factors tending to reduce survival, the mortality of cod was negligible and that of haddock less than 10%. Other species such as herring (*Clupea harengus* L.) may be more sensitive to gear damage (Suuronen, 1991) than are gadoids. These gadoid species, at least in the size groups relevant for the mesh sizes used in the Norwegian bottom trawl fisheries, therefore seem to survive the selection process well. However, considerable amounts of 0- and 1-group gadoids are caught and released from small-meshed gears such as shrimp trawls. The survival of these small fish is unknown, and should be studied in detail in further experiments.

It has been claimed that the mesh selection concept for conserving undersized cod and haddock is not worthwhile because of high mortality owing to escapement (Zaferman and Serebrov, 1989). The results presented here show that a high survival rate can be expected from gadoid species that escape from a demersal trawl.

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Escapement and survival of fish from the codend of a demersal trawl

Joseph T. DeAlteris and Daniel M. Reifsteck

DeAlteris, J. T., and Reifsteck, D. M. 1993. Escapement and survival of fish from the codend of a demersal trawl. – ICES mar. Sci. Symp., 196: 128–131.

The escapement and survival of juvenile fish from square and diamond mesh codends was investigated for three fish species: scup (*Stenotomus chrysops*), winter flounder (*Pseudopleuronectes americanus*), and Atlantic cod (*Gadus morhua*). A towed codend simulation apparatus (TCESA) was developed to investigate escape behaviour and determine survival probability. With respect to square- and diamond-mesh shape selectivity, no significant difference was observed in the L_{50}s for scup, but a significant difference was found for winter flounder and Atlantic cod. The survival of codend escapees was excellent, with no significant differences observed between control and square- and diamond-mesh-treated fish. Only scup were observed to be active swimmers in the codend. Irrespective of swimming activity, escape time was reduced significantly with square mesh for most species tested.

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Introduction

Minimum mesh-size regulation is the primary method of regulating trawl fishing mortality on juveniles in a fish stock. The basic principle of minimum mesh size regulations is that undersized fish that escape from the codend survive, and become part of the future spawning biomass of the population.

Selectivity can be considered as any factor that causes the size or species composition of the catch to be different from that of the population, or that causes fishing mortality to vary with size (or other characteristics) of the fish (Pope *et al.*, 1975). Size selection of fishes in the zone of a demersal trawl occurs predominantly in the codend. Factors that affect fishing selectivity are gear type, fishing methods, tow duration, area fished, as well as the sex, size, shape, and behaviour of the particular fish (Margetts, 1956, 1963; Clark, 1960, 1963).

Control of selectivity is considered an important management tool because certain gears are size selective on a population. It is widely accepted that adjustment of mesh size in nets to permit escapement of fish below a chosen size contributes optimum yields for species harvested by trawl gear.

The process of fish capture and escape from a trawl net presumably induces an acute stress and has been associated with mortality (Dando, 1969; Miles *et al.*, 1974). The potential mortality of escapees may be related to the physical damage such as abrasions, lacerations, and contusions that a fish may incur within the net or during escape. Mortality may also occur because of physiological stress associated with hyperactivity and the resulting conditions.

The objectives of this study were to:

1. Establish selectivity ogives for the three test species fished with diamond and square mesh trawl codends, so as to determine a suitable size range for the investigation of escapee survival for these species as a function of codend rigging.
2. Determine the survival probability of escapees as a function of codend rigging, swimming time, and escapement time.
3. Investigate the behaviour of fish within the codend to better understand how behaviour may influence the escape and survival of fish from the codend.

Methods

To examine the question of the survival of codend escapees, a towed codend simulation apparatus (TCESA) was developed to duplicate the codend environment. This device consisted of a swimming chamber tapering to a codend, which was enveloped in a small-mesh cover, all of which was attached to a towing sled. The codend webbing was 12.0 and 12.6 cm stretched mesh length with a 4 mm diameter; the codends were hung with both traditional diamond-mesh and square-mesh shapes (Fig. 1).

The TCESA was evaluated for its hydrodynamic equivalency to a bottom trawl in a circulating water channel at the David Taylor Naval Ship Research and Development Facility in Bethesda, MD, USA, and was found to simulate a trawl codend; furthermore, the small-mesh cover did not significantly affect the flow in the codend (Reifsteck and DeAlteris, 1991).

Three species of fish were tested: scup (*Stenotomus chrysops*), winter flounder (*Pseudopleuronectes americanus*), and Atlantic cod (*Gadus morhua*). The size range of fish treated in the TCESA was determined by conducting size selectivity experiments using a small-mesh cover over the square- and diamond-mesh codends. Based upon the selectivity curves generated from these data, fish sizes ranging from 5 to 30% retention were selected for the survival experiments. Experimental fish for the survival experiments were captured with hand lines using barbless hooks, and were subsequently allowed to acclimate in captive holding tanks or pens from half a day to several days until being treated in the TCESA.

Each trial consisted of two actions. From the capture tank one individual was transferred to a control tank and another individual was introduced into the mouth of the TCESA by a diver. Towing speed was maintained at 128 cm s^{-1}. Tow duration was as long as the fish required to escape or a maximum of 30 min. At that time the trial was terminated, the towing vessel was stopped, and the fish was allowed to escape through the slack codend webbing. The escapee was immediately removed from the cover and carefully transferred into the treatment tank of the towing vessel. Observations of fish behaviour in relation to the webbing were recorded by a diver. At the culmination of the experiments, the treated and control fish were placed in separate cages on the seabed in 5–10 m water depths to begin a 10-day monitoring period.

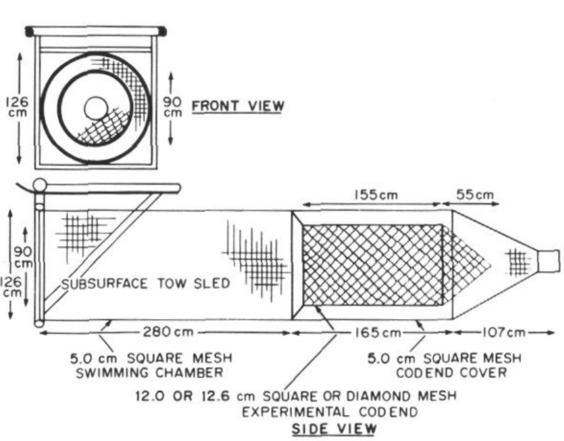

Figure 1. Front and side views of a towed codend simulation apparatus (TCESA) designed to duplicate the codend environment of a fishing net. Swimming chamber and cover are constructed of square mesh 5.0 cm stretched mesh length. The square- and diamond-mesh codends are interchangeable and constructed of double twine 4 mm in diameter with a stretched mesh length of 12.0 and 12.6 cm.

Quantitative data collected in the survival experiments included total swimming time and escapement time for each treatment fish and percent survival for each treatment group. Escape time was the total elapsed period the treated fish was in the TCESA prior to escape. The swimming time was the duration of active swimming while the treated fish was in the TCESA. The difference between escapement time and swimming time was the total time the treated fish was against the webbing in the TCESA. Analysis of variance was used to determine whether significant differences ($\alpha = 0.05$) existed between the escapement time and survival as a function of mesh shape.

Results

Based on the selectivity experiments conducted using the covered codend method, the L_{50}s for 12.0 cm stretched length square- and diamond-mesh codends on scup were similar at 21.6 and 21.1 cm, respectively. The L_{50}s for 12.0 cm stretched length square- and diamond-mesh codends on winter flounder were 20.8 and 23.6 cm, respectively. The L_{50}s for 12.6 cm stretched length square- and diamond-mesh codends on Atlantic cod were 47.8 and 55.2 cm, respectively.

The survival probability for scup was determined over a three-year experimental period (Table 1). The mean survival probability for the first year (1988) of experiments was 94 and 50% for the square and diamond mesh, respectively, and these were significantly different. Survival for control fish was approximately 95% and this was significantly different from the diamond-mesh treatment. In the second year (1989) the mean survival probability for square and diamond mesh was 100 and 97% respectively; and these were not significantly different. Survival of control fish was 100% and neither of the treatments was significantly different from the control. The survival of scup in the third year of experiments was 100% for both square- and diamond-mesh treatments, and controls.

The survival probability for winter flounder was investigated over a two-year period (Table 2). During the first year, the mean survival probability was 100 and 96% for square and diamond mesh, respectively; and these were not significantly different. Survival of control fish was 100% and neither treatment was significantly different from the control.

The survival probability of Atlantic cod was investigated over a two-year period (Table 3). During the first

Table 1. Results from square- and diamond-mesh trials of juvenile scup (*Stenotomus chrysops*) in Narragansett Bay, Rhode Island.

	No. of fish	Mean total length (cm)	Mean swimming time (min)	Mean escape time (min)	Per cent survival
1988					
Control	36	–	–	–	100
Square-mesh treatments	34	17.5	9.1	11.5	94
1988					
Control	37	–	–	–	89
Diamond-mesh treatments	32	17.4	17.8	19.7	50
1989					
Control	38	–	–	–	100
Square-mesh treatments	38	16.9	5.3	9.6	100
1989					
Control	35	–	–	–	100
Diamond-mesh treatments	35	16.5	6.2	13.6	97
1990					
Control	22	–	–	–	100
Square-mesh treatments	22	16.9	3.4	11.2	100
1990					
Control	27	–	–	–	100
Diamond-mesh treatments	27	17.3	7.4	16.3	100

Table 2. Results from square- and diamond-mesh trials of juvenile winter flounder (*Pseudopleuronectes americanus*) in Narragansett Bay, Rhode Island.

	No. of fish	Mean total length (cm)	Mean swimming time (min)	Mean escape time (min)	Per cent survival
1989					
Control	38	–	–	–	100
Square-mesh treatments	38	16.4	0	11.3	100
1989					
Control	29	–	–	–	100
Diamond-mesh treatments	28	16.4	0	17.1	96
1990					
Control	20	–	–	–	100
Square-mesh treatments	20	17.7	0	12.8	95
1990					
Control	20	–	–	–	100
Diamond-mesh treatments	20	17.6	0	11.3	85

and second years, the mean survival probability was 100% for both square- and diamond-mesh escapees, and the survival of control fish was also 100%.

Behaviour within the codend was also evaluated to examine the effect of mesh shape on swimming time within the codend and on escape time from the codend. For scup in 1988, swimming time and escape time were significantly longer in the diamond-mesh treatments. In 1989, escape time was significantly longer for diamond-mesh treatments, but there was no significant difference in swimming time between the square- and diamond-mesh treatments. In 1990, there were significant differences in both swimming time and escape time between square and diamond mesh. For winter flounder, the treated fish were never observed swimming in the codend, and there were no significant differences in escape time between square and diamond mesh. For Atlantic cod, fish were only rarely observed swimming in the codend and then only for brief periods. In the first year of experiments, there was a significant difference in mean escape time as a function of mesh shape; however, in the second year, there was no difference.

Table 3. Results from square- and diamond-mesh trials of juvenile Atlantic cod (*Gadus morhua*) in Cape Cod Bay, Massachusetts.

	No. of fish	Mean total length (cm)	Mean swimming time (min)	Mean escape time (min)	Per cent survival
1990					
Control	29	–	–	–	100
Square-mesh treatments	29	44.4	0.6	5.9	100
1990					
Control	31	–	–	–	100
Diamond-mesh treatments	31	42.4	0.2	12.4	100
1991					
Control	5	–	–	–	100
Square-mesh treatments	5	41.2	0.0	7.7	100
1991					
Control	10	–	–	–	100
Diamond-mesh treatments	10	40.8	0.0	6.6	100

Discussion and conclusions

Based on the experiments conducted, codend escapee survival appears to be reasonably high (except for the first year experiments on scup and these are attributed to extremely high water temperatures during the post-treatment monitoring period), and not related to mesh shape. For some species of active swimming fish, square-mesh shape provides a larger opening that leads to a shorter escape time for the small fish, thus presumably reducing the stress placed on the fish during the capture/escape process. The results of these experiments provide the scientific evidence required to substantiate the validity of minimum mesh-size regulations for the three species evaluated, and the corresponding minimum fish-size landed regulations, as a means to reducing fishing mortality on juvenile fish.

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II. TECHNIQUES OF OBSERVATION

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A review of techniques for the observation of fish behaviour in the sea

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Urquhart, G. G., and Stewart, P. A. M. 1993. A review of techniques for the observation of fish behaviour in the sea. – ICES mar. Sci. Symp., 196: 135–139.

During the past 25 years there have been significant developments in the resolution and sensitivity of the instruments available for investigating fish behaviour in the sea. This paper reviews the principal techniques and instruments which have been devised. There are three main approaches: direct observation by humans, indirect observation using cameras, and the use of acoustics. Manned and unmanned vehicles are used to transport both divers and cameras close to the fish. Acoustics permits observation at greater range and is most useful for observing shoals of fish and tracking tagged individuals. The limits to performance of various methods are considered and development trends are discussed.

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Introduction

The reactions of fish to fishing gears have long been of interest to fishermen and fisheries scientists. Without the ability to observe their behaviour directly in the sea, knowledge could be gained only by slow and careful experimentation, investigating the effect on catch size and composition of varying the construction of the gear. Although progress by such empirical means was slow because of the high variability in catches, useful theories were developed about how fish were herded by trawls and seines and how they could escape capture (Wardle, 1983).

This paper concentrates on some technical developments of the last 25 years that have enabled fish behaviour in the sea to be studied more closely, especially by scientists. Three main approaches have been used: (1) direct observation by humans, (2) indirect observation with television, cine, and still cameras, and (3) fish detection and monitoring by acoustics.

Divers

Direct observation underwater by humans is invaluable in the study of fish behaviour. Although diving observations are restricted by depth, time, and visibility, divers' ability to react gives them a versatility that no machine can match. During lobster behaviour experiments, for example, a diver may replace an animal in precisely the same location as it was caught, and only divers could undertake the detailed assessment of damage to young gadoids escaping a trawl (Main and Sangster, 1990). The presence of divers may affect the way in which fish react; Chapman and Atkinson (1986) found the effect to be complex.

The scientific diving community uses SCUBA diving techniques almost exclusively. Statutory regulations in the UK, for all practical purposes, limit diving to a depth of 30 m. At this depth, the maximum time a diver can spend is normally 20 min. Multiple dives are even more severely restricted, limiting total diving time per day to just an hour or two.

Despite these restrictions, direct observation by divers has considerable value. With appropriate equipment, it becomes possible to take measurements and record data. A device specifically developed for fish behaviour work was the voice recorder back-pack which allowed counts and descriptions of behaviour to be logged continuously (Chapman *et al.*, 1979).

Cine, still, and TV cameras have all been used to record fish behaviour. Wardle and Hall (in press) review the video equipment available and Wardle (1983) describes its use to study the reactions of fish to towed fishing gear. Film cameras and conventional TV tubes and CCD (charge coupled device) detectors, both with and without intensifiers, can be used to give a wide range of sensitivity and spectral response. Table 1 summarizes the relative performance of the principal types of underwater camera at varying light levels.

At one extreme, in shallow, clear water, or at close range using artificial light, high-quality colour pictures may be obtained on film and by TV. Owing to differential absorption of different wavelengths of light, colour photography becomes increasingly ineffective with increasing range, and has a practical limit of a few metres. Greater ranges are possible with black-and-white photography. Physical size, weight and power requirements increase with camera sensitivity; the most sensitive ISIT (intensified silicon intensified target) cameras are normally too large for a free diver to handle. CCD cameras without intensifiers run from a low-voltage DC supply, and camcorders incorporating CCD detectors packaged for the leisure diving market are already available.

Manned submersibles

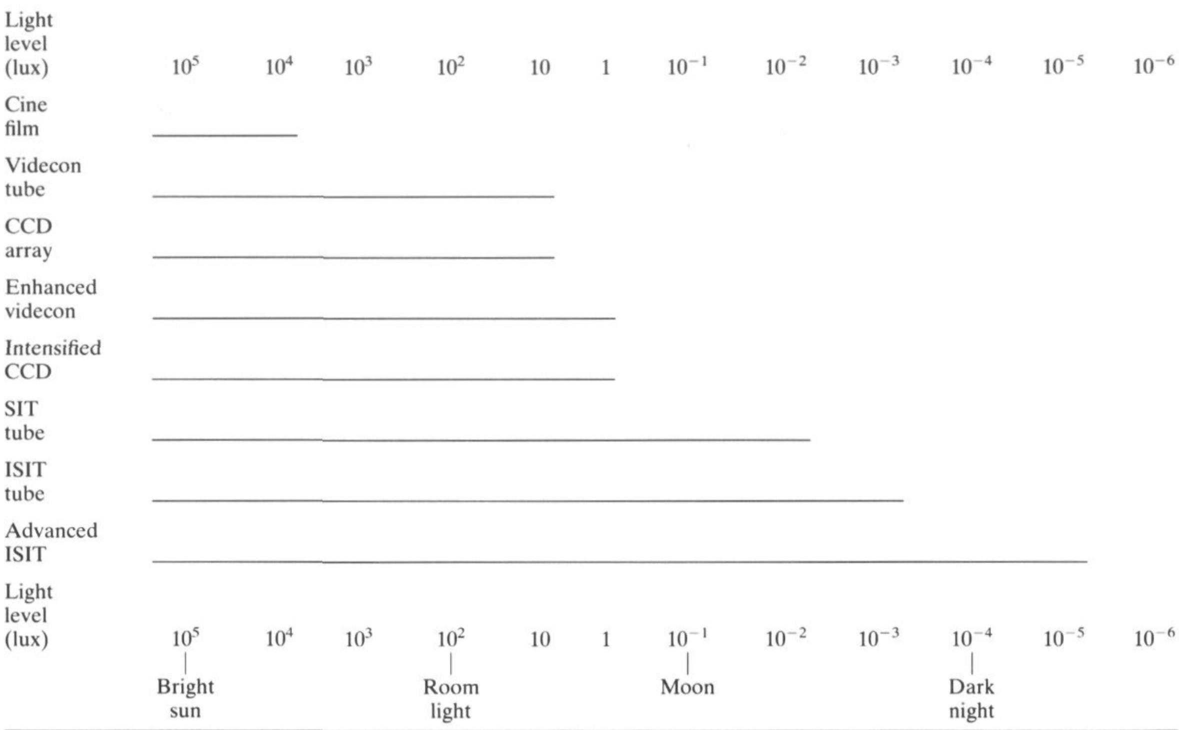
At 30 m and deeper, the natural light level is generally too low for all but the most sensitive cameras. Their large size demands rigid mounting. Manned submersible vehicles for general biological research have been reviewed by Gilchrist *et al.* (1983). A number have been tested by fisheries scientists but none has been adopted. The diver's towed vehicle, which is still used by Main and Sangster (e.g. 1983) was specifically designed to carry and protect divers engaged in the observation of fish and fishing gear. Although normal SCUBA limitations apply, the vehicle allows high-quality filming using almost any camera system (Fig. 1).

Unmanned submersibles

Unmanned submersibles are more numerous than the manned variety (Gilchrist *et al.*, 1983) and find a wider application in fisheries investigations. They offer advantages of lower cost, greater depth and dive duration, and a greater ability to operate in hostile conditions. Three main types are used by fisheries scientists: towed bottom sledges (Chapman, 1985), towed vehicles with depth and lateral control (Priestley *et al.*, 1985) (Fig. 2), and remotely operated vehicles (ROVs) with three degrees of freedom but on an umbilical cable.

A variety of bottom-mounted frames and platforms (Johnstone and Hawkins, 1981), drop vehicles (Priede and Smith, 1986), and suspended arrangements have also been used to carry instruments. Camera and instrument packages are sometimes attached directly to the headline of a net and to samplers and other devices to see how they affect fish. Self-contained packages using

Table 1. The performance of underwater cameras with varying light level.



The table gives a broad comparison of the relative performance of the main types of camera. The horizontal lines indicate the estimated range of performance or the performance limits claimed by manufacturers.

Figure 1. Photograph taken from the diver's towed vehicle showing saithe, *Pollachius virens*, swimming ahead of the mouth of a trawl. The low-light TV camera seen on the right is used by a diver to record the behaviour of the fish with much greater clarity than can be captured on film.

CCD cameras and small video recorders continue to be developed for net mounting. Another recent development has been the transmission of video by radio, such as the VISION LINK system by Optex. This has been used to transmit pictures of fish over several kilometres, by means of an underwater camera connected to a transmitter buoy at the surface.

Acoustic detectors

Echo sounders and sonars are widely used devices for fish detection (Mitson, 1983; MacLennan and Simmonds, 1992). Frequencies in the range 15 to 500 kHz are used, but attenuation increases with frequency, reducing detection range. The divergence of the acoustic beam is determined by the width of the transducer relative to the wavelength; wide transducers give narrow beams and better focusing of the acoustic energy. Information is wanted on the movements of both shoals and individual fish. With appropriate parameters for the target range, echoes from individual fish can be distinguished. Since it is often difficult to separate targets, acoustic observation is more suitable for shoals than individuals.

Fish with swimbladders are better reflectors of acoustic energy than those without. Typical fish shape results in the target strength being highly dependent on the angle of the incident acoustic wave. Thus a single echo reveals little about the size or orientation of a target fish. With a conventional, vertically transmitting echo sounder and a fish maintaining a near-horizontal attitude, however, there can be enough consistency in echo patterns to study behaviour. Normally, many echoes from a single fish must be combined to obtain amplitude distributions and mean values which can be usefully interpreted. A recent development which expands the capability of vertical sounders is the split beam technique (Foote, 1988). This enables the bearing and range of a target within the beam to be measured. Several fish at similar ranges can be distinguished and tracked whilst within the beam. The technique can provide information on vessel avoidance reactions. With sonars, scanning at various angles, reflectivity is generally too inconsistent to track individuals, but shoals can be studied. Echo traces from shoals of particular species often have characteristic forms, and pattern recognition techniques are now being applied to identify species with greater certainty.

A number of studies have taken place using an active sonar together with transponding tags designed to receive transmissions and send back a powerful pulse clearly identifying the target. Mitson and Storeton-West (1971) describe the technique, and a list of references relating to the application of the system appears in

Figure 2. The Aberdeen Marine Laboratory's unmanned, towed, remote controlled vehicle alongside a net. Vertical and lateral control is achieved with Magnus rotors (spinning cylinders). The vehicle carries TV cameras, still cameras and other instruments to study gear performance and fish behaviour.

Arnold *et al.* (1990). In shallow, inshore areas, transponding tags used with more conventional sonars have been less successful owing to the presence of strong and complex echo returns from the surface, shore, and bottom targets.

Acoustic transducers are most commonly mounted on ships' hulls but can be mounted remotely from the processing electronics with cable or acoustic links. Particularly useful are "netsondes", with either fixed or mobile transducers, which can be mounted on nets to detect fish. Such devices can be placed near set-nets or traps to observe fish movements (Inoue and Arimoto, 1988). With mobile fishing gear it is important to have a display that updates rapidly to obtain distinct fish echoes. Side-scan sonars can produce longer-range information on the distribution of fish shoals in an area.

Acoustic tags

Only one technique is known that gives reliable, continuous, long-term information about the movements of invididual fish beyond the range of low-light TV observations. This is acoustic tagging: attaching sonic transmitters to individuals so that the output signals can be detected and used to locate the fish. The technique was first described by Johnson (1960) and has been reviewed by Hawkins and Urquhart (1983). Capture and handling may cause trauma to the animals, but evidence shows that when tags are inserted in the stomach, most fish resume normal behaviour less than 24 h after tagging. The effects of external tagging have been studied by Arnold and Holford (1978) and by Lewis and Muntz (1984).

Migrating fish with acoustic tags must be tracked from a vessel with a directional receiver. The receiver is moved either mechanically or by hand to gain maximum signal strength, and measurements or estimates are made of range and bearing. Smith *et al.* (1981) used this technique to study the coastal movements of salmon. With the fish at a range of 50 to 100 m, migration routes were obtained from surface radio-navigation data.

Non-migratory fish living inshore are best studied using pulsed tags and an array of hydrophones (Johnstone *et al.*, 1991; Urquhart and Smith, 1992). A similar system by VEMCO recently delivered to fisheries scientists in Norway uses radio buoys which can be continuously redeployed around the path of a migrating fish.

Future developments

In each of the main areas discussed, there are developments and prospects of progress. Oxygen-enriched air diving (Nitrox) offers real improvements in safety and increased diving time together with closed-circuit operation. Surface demand techniques have hardly been explored at all by scientific divers and may offer advantages.

Underwater vehicles, mainly unmanned, continue to be developed by fisheries institutes. Other vehicles like the proposed Seametrix Ocean Surveyor 3000 will combine the virtues of a towed vehicle with the mobility of an ROV. Underwater instrumentation is likely to continue to improve. Low-light cameras are already operating at photon/electron level close to physical limits, but there are developments in the fields both of image intensifiers and of detectors, particularly CCD arrays. A limitation at present is that all videcon tubes and intensifiers need high-voltage supplies. CCD cameras without intensifiers can run from a low-voltage DC supply.

Because acoustic transducers tend to be large and expensive, most fish behaviour studies using sonar have been made at single frequencies. By varying frequency, more could be learnt about fish targets, because the frequency dependence of target strength is likely to be related to species (Simmonds and Armstrong, 1990). Continuing improvement in data-processing methods opens up possibilities for constructing more complex devices for use underwater, remote from the ship. The methods that enable aircraft to identify moving targets from amongst ground clutter may be applicable to net-mounted sonar to track fish well ahead of a net.

Radio buoys could bring improvements in acoustic tracking systems where cables are now used, and the precision of tracking could be improved by adopting simple frequency shift keying (FSK) techniques. Multi-frequency, digital, FSK systems developed for through-water telemetry in the offshore oil industry may lead to reliable telemetry of data from fish if the problems of miniaturization can be overcome.

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The upgrading of a Mermaid underwater vehicle

D. de Haan

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Dutch research on development of direct observation techniques started with the purchase of an underwater towed vehicle of type "Mermaid Explorer" in 1985. Targets for further development were observation of a wider range of fishing gears, with speeds up to 7 knots, and inspections of the marine environment requiring low-speed operation. A feasibility analysis showed the potential of an increase in magnus rotor performance. The single towing mode will be extended by a propelling mode (hovering mode). The two modes are to be interswitched without paying back. Performance measurements on several rotor configurations were conducted as part of the vehicle design process. A cross lay-out with four rotors reached the greatest depth in the shortest amount of time. A spherical rotor appeared to be ineffective.

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Introduction

RIVO started its direct observation programme with the "Mermaid Explorer" underwater vehicle in 1985. The prototype was designed by the Marine Laboratory, Aberdeen (Priestley *et al.*, 1985). After two years of operation it became clear that future demands in research would not be covered by the scope of the original "Mermaid Explorer".

In 1987 a strategy to increase the scope was defined in cooperation with Seatec (a private company). The main features of this strategy are improvement of the performance of magnus rotors (phase 1), development of an umbilical winch system (phase 2), and development of a static propelling mode (phase 3).

In 1989 the first phase, a hydraulic rotor-drive, became available for tests and measurements. The next phase became available in 1991 after commissioning the new RV "Tridens". The ROV system was extended with a removable umbilical winch, containing a 1200 m umbilical cable 24 mm in diameter.

Definition of tasks

There are two related fields in which underwater observations are required: (1) fisheries research, and (2) environmental inspections.

Fisheries research

In Holland, underwater observations are required on a wide range of different gears: beam trawls (speeds from 4 to 7 knots); pelagic trawls (up to 1000 m behind the vessel); slow-speed trawls, such as Danish seines and pair seines (speeds around 2 knots); and static gears, such as drift and set-nets.

Environmental inspections

New requirements in fisheries research are to investigate and inspect the marine environment. Two examples are the study of the impact of fishing gear on benthic organisms, and the impact of beam trawling on offshore constructions and vice versa. At present, research has to be carried out from at least two ships. The interswitchable hovering/towing mode enables the use of only one ship. These requirements define the operational profile as: (1) a towing mode with a speed range from 2 to 7 knots, and (2) a hovering mode with a speed range from 0 to 2 knots. The hovering mode will enable an immediate reaction when the towing speed drops to zero, as in the case of gear fasteners.

The original "Mermaid Explorer" cannot execute both tasks. The available power (1 hp per rotor pair) is not sufficient to generate the desired rotor forces.

Some theoretical tests

Theoretical work on magnus rotors (Tietjens, 1934) reveals the potential to increase rotor performance by increasing the rotor dimensions and number of revolutions.

The generated lift force of a magnus rotor is proportional to the ratio of $U_0 {*} V^{-1}$, where U_0 is defined as the rotor surface velocity and V as the towing velocity. The rotational speed U_0 is expressed in the equation:

$$U_0 = n * 2 * \pi * D$$

where n = rotor revolutions per second and D = rotor diameter in m. The various research objectives result in different values of $U_0 {*} V^{-1}$. Tietjens (1934) shows the relationship between the lift and drag coefficients and the ratio $U_0 {*} V^{-1}$. The maximum rate of increase in lift is found for $U_0 {*} V^{-1} \leq 3$.

To find the corresponding lift and drag forces the lift and drag coefficients are substituted into the next equations:

Lift force: $F_L = 0.5 * \rho * V^2 * D * L * C_L$

where ρ = water density (104 $kg.s^2.m^{-4}$), V = towing speed in m s^{-1}, D = rotor diameter in m, L = rotor length in m, and C_L = lift coefficient.

Drag force: $F_D = 0.5 * \rho * V^2 * D * L * C_D$

where C_D = drag coefficient.

Figure 1 shows results of calculations of the vector diagrams of lift and drag forces for three rotor types at two towing velocities of V = 3 knots or V = 7 knots. Rotor types 1 and 2 had end discs 0.25 m in diameter, and type 3 0.3 m in diameter. Type 1 was the original Mermaid rotor with diameter 0.148 m, length 1.1 m and $U_0 = 3.09$ m s^{-1} at 400 rpm. Type 2 was the same rotor with $U_0 = 4.65$ m s^{-1} at 600 rpm. Type 3 was the new Mermaid rotor (not yet used on a vehicle) where diameter was 0.2 m, length was 1.2 m, and $U_0 = 6.28$ m s^{-1} at 600 rpm.

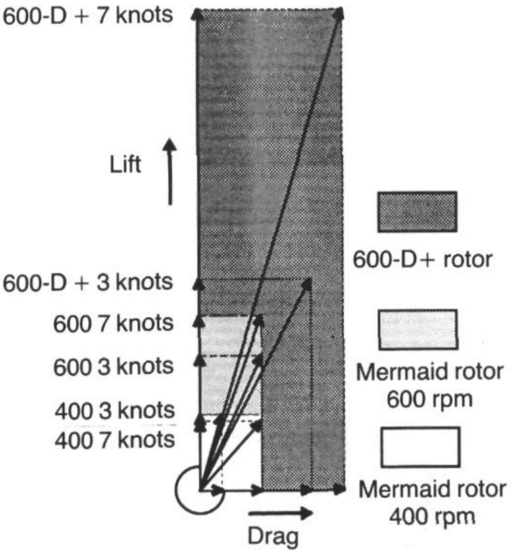

Figure 1. Vector diagram of the lift and drag forces.

The present hydraulic Mermaid vehicle

In the present Mermaid vehicle the rotors of type 2 are arranged as horizontal and vertical pairs in a cross configuration. Each rotor pair is driven by a serial chain of two hydraulic motors. Each motor chain is supplied by a hydraulic pump. The two pumps are powered by an electric motor (6 kW, 660 V). The total power needed to drive all four type-2 rotors is 2 kW and this requires at least a 3 kW electric motor with a system efficiency of 0.7. Spare electric motor power will be used to drive rotor type 3 and can be employed to drive a third pump used for accessories such as the pan-and-tilt drive.

Advantages of a hydraulic system

Increasing the power from 3 to 6 kW has led to an increase of weight in air from 230 kg to 400 kg. However, it is more efficient to run one hydraulic power pack than several electric motors to do the same tasks. Other advantages are:

- one energy source for all operational modes
- flexibility in arrangements of rotors and future thrusters
- high performance with smaller dimensions
- simplified remote control
- reduced number of umbilical wires
- flexibility of extending the system

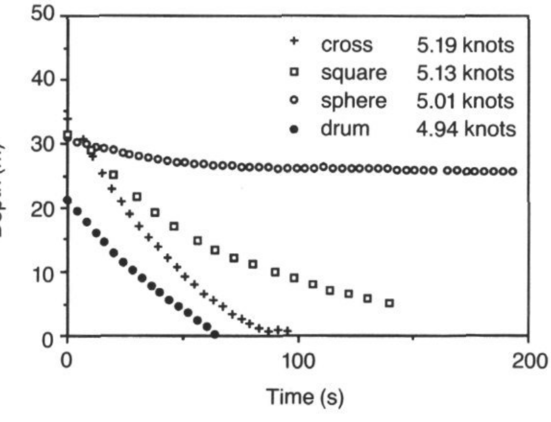

Figure 2. Performance of various magnus rotors.

Finding the best rotor arrangement

To find out whether we had the best performance, four different rotor arrangements were investigated using the vehicle, described in section 4, as the test platform. The results of the tests, shown in Figure 2, were obtained using a 200 m clip cable system towed at 5 knots. The rotor configurations were: cross, four type-2 rotors in the familiar cross configuration; square, four type-2 rotors arranged to operate in a square configuration; sphere, a single spherical rotor with a diameter of 0.68 m operated at 237 rpm; drum, a single larger cylindrical rotor with a diameter of 0.6 m, length 0.8 m, with end discs of 0.9 m diameter and $U_0 = 5.78 \text{ m s}^{-1}$.

Depth was measured as a function of elapsed time under full-power condition starting from the unpowered towing depth. Time was stopped when the surface was reached. Results of the measurements are shown in Figure 2.

The lower performance of the square configuration can be explained by the mutual distortion of the stream pattern behind the magnus rotor. Therefore the buoyancy has been repositioned and replaced by floats. The hydraulic power source has been repositioned behind the attachment point of the umbilical. The repositioning has led to an improvement in lateral displacement. Measurements using the reference of the spread between both doors of a bottom trawl showed an increase in lateral displacement to around 70 m at an umbilical length of 150 m. Data recorded with Scanmar spread sensors fitted to both the ROV and the other boards of a bottom trawl are presented in Figure 3. In this example the measurements were started with the vertical rotors switched off, and when the vehicle position was stable the vertical rotors were switched to full power. In this case the vehicle was fitted with rotor type 2 in cross configuration, the towing cable was 300 m and towing speed was 5 knots. The track between the time markers presents the movement of the ROV under full power.

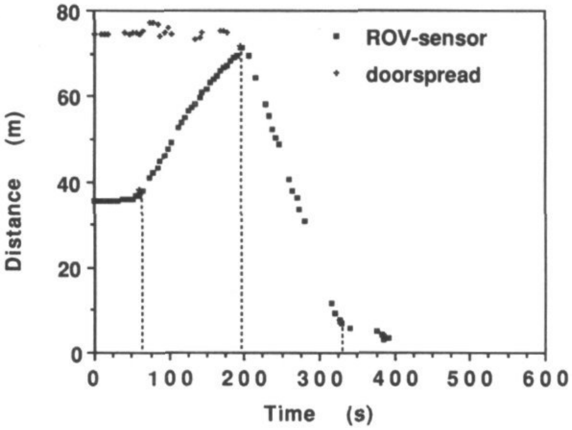

Figure 3. Lateral displacement with rotor type 2 in cross configuration, 300 m cable, and towing at 5 knots.

Conclusions and recommendations

At 7 knots the original rotor (type 1) has the lowest efficiency. The efficiency of the present Mermaid rotor (type 2) at 600 rpm proved to be constant at both speeds. Although the performance of the 600-D+ rotor has not been recorded, the vector diagram shows its potential for generating high forces. At 7 knots the 600-D+ rotor produces the highest lift vector, while the resultant force shows the same angle as the type 1 rotor at 3 knots. To improve efficiency at slow speeds it is recommended to select a maximum rotational speed for different types of fishing gear. To compare the improvement of the lateral displacement the performance of the original Mermaid should be recorded. The drum rotor configuration shows potential to reduce the total drag of the ROV. The sphere configuration proves to be ineffective. When the square configuration is further optimized, a reduction of total vehicle dimensions might be expected, or an increase of performance by increasing length within the existing surrounding frame dimensions.

Acknowledgements

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Local movements of saithe (*Pollachius virens* L.) in the vicinity of fish farm cages

Åsmund Bjordal and Alastair D. F. Johnstone

Bjordal, Å., and Johnstone, A. D. F. 1993. Local movements of saithe (*Pollachius virens* L.) in the vicinity of fish farm cages. – ICES mar. Sci. Symp., 196: 143–146.

Saithe (*Pollachius virens* L.), are commonly observed in the vicinity of sea cages at fish farm sites and are known to feed on excess food pellets. This study monitored movement patterns of saithe around fish farm cages to evaluate temporal distribution of the fish and to assess the impact of fish farms on wild populations. To investigate the local movements of saithe, an acoustic position-fixing system was established in the vicinity of a fish farm at Austevoll on the west coast of Norway during September and October 1991. Nine saithe (490 to 560 mm total length) were externally tagged with individual ultrasonic transmitters and their movements were tracked for periods of 16.6 to 264 h. The tracked saithe were active during the day but were relatively inactive at night, restricting their movements to a core area. On several occasions fish with acoustic tags were observed feeding at the surface within groups of up to several hundred other saithe. The tracked saithe could be classified into two groups according to their movement patterns. The fish either had a home range with the cages as the core area, or had a core area in deeper water further offshore and visited the fish farm site on a daily basis. Some of the fish also visited an adjacent fish farm but generally returned to their core area by nightfall.

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Introduction

Saithe (*Pollachius virens* L.) are one of the commonest fish found in northern European inshore waters. They are often observed in the vicinity of sea cages at salmon farm sites and are known to feed on excess food pellets.

The aggregation of wild fish, such as saithe, around fish farm cages in inshore waters may alter local fish distribution and cause reduced availability at traditional inshore fishing grounds. Fish farms can act as exclusion zones and thus affect the catch rates of local traditional commercial and recreational fisheries. The effects of fish farming on the distribution and behaviour of wild fish stocks have previously been investigated by biological sampling and conventional tagging techniques. Carss (1990) describes the occurrence of a variety of gadoid species around marine farm cage sites. The occurrence of salmon lice on saithe associated with fish farms has been reported by Bruno and Stone (1990) and there is a general concern that indigenous fish may act as vectors of pathogens between fish farms (Samuelsen *et al.*, 1992). Although evidence derived from the results of conventional tagging experiments (Bjordal and Skar, 1992) exists for the migration of saithe between fish farms, detailed local movements of marine fish associated with fish farms have not been described previously.

The use of acoustic telemetry to track saithe has been described previously by Johnstone *et al.* (1991) and Glass *et al.* (1992). The present study observed the movements of saithe fitted with acoustic transmitters in association with a fish farm on the Norwegian west coast.

Materials and methods

The investigation was conducted at one of the sea cage sites of the Austevoll Aquaculture Research Station, near Bergen, Norway, during the period 26 September to 18 October 1992. An array of five hydrophones linked to a position-fixing system on shore was established around cage site A (Fig. 1). The cage site comprised 14 (12 × 12 m) floating cage frame units. Three of the

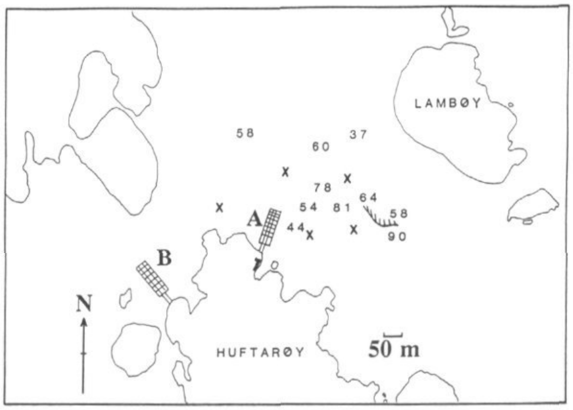

Figure 1. Diagram of the study area at Austevoll. The positions of the five tracking system hydrophones (X) and the cage sites A and B are shown. Selected depth soundings are given in metres, and an underwater ridge or cliff is indicated with a hatched line.

frames had net pens (6 m deep) containing juvenile and adult Atlantic salmon (*Salmo salar* L.) and juvenile cod (*Gadus morhua* L.), all of which were fed automatically on a daily basis with dry pelleted food during the study period.

The study location was situated in a basin, sheltered from the neighbouring fjord system by several small islands. As indicated in Figure 1, there is a trench of 60–90 m depth in the middle of the area (between Huftarøy and Lambøy). The trench is partially bordered by an underwater rock outcrop or cliff rising to 20 m above the seabed. This feature was discovered during an underwater television survey of the study area.

Saithe for tagging were captured either by being enticed by food pellets into an empty sea cage and trapped or by angling at the cages with a baited, barbless hook and line. Nine saithe of 490 to 550 mm (total) length were caught and tagged during the study (Table 1). The fish were anaesthetized before being tagged in a 5 mg l^{-1} seawater solution of Metomidate HCl (Norsk Medisinaldepot). Ultrasonic transmitters (MAFF, Lowestoft, UK), each with a unique combination of output frequency and pulse repetition rate, were attached to each fish at the base of the first dorsal fin by the anchors of two Floy tags fastened to each end of the transmitter case. The fish were allowed to recover in sea water before release at the place of capture. Fish D was fitted with an alternative pressure-sensing transmitter (Vemco Ltd, Nova Scotia, Canada) which relayed data on swimming depth during tracking.

The fixed hydrophone array and tracking system was described by Hawkins and Urquhart (1983) and more recently by Urquhart and Smith (1992). An additional manual tracking system with a hand-held receiver (CAI Ltd) was used from a boat to locate fish which moved beyond the detection range of the fixed hydrophone array. Another receiver linked to an automatic listening station (Argus Electronics, Norfolk, UK) was established at the adjacent cage site B (Fig. 1) to record remotely the presence of tagged fish.

At the end of the study period, saithe were captured at site A by trapping a group during the day and removing a sample of 51 fish which included one of the fish with an acoustic tag (fish H). Length, age, weight, sex, maturity, and stomach contents were determined for each of the sampled fish.

Results

The tagged saithe were tracked for periods ranging from 16.6 to 264 h, but not always on a continuous basis. The range for detection of signals from the acoustic tags by the hydrophones was approximately 500 m under calm sea conditions. However, accurate position fixes were only obtained when signals were detected on a minimum of three hydrophones.

Up to five fish were tracked simultaneously. During direct visual observations some of the tagged fish were seen swimming and feeding within shoals of saithe, and their behaviour appeared normal. On other occasions shoals of saithe, including fish with an acoustic tag, were observed immediately under the cages by underwater television. Tagged fish were never seen in isolation.

Table 1. Size and tracking time of the nine saithe studied (A-I).

Saithe	Total length (mm)	Start of track		Track duration (h)
		Date	Time	
A	500	26 Sep 1991	19:45	230.25
B	500	28 Sep 1991	15:48	228.47
C	490	28 Sep 1991	15:48	264.09
D	550	02 Oct 1991	15:20	16.62
E	500	07 Oct 1991	19:27	253.85
F	520	09 Oct 1991	19:10	207.86
G	560	11 Oct 1991	19:37	82.99
H	510	14 Oct 1991	09:47	98.30
I	535	14 Oct 1991	19:08	89.10

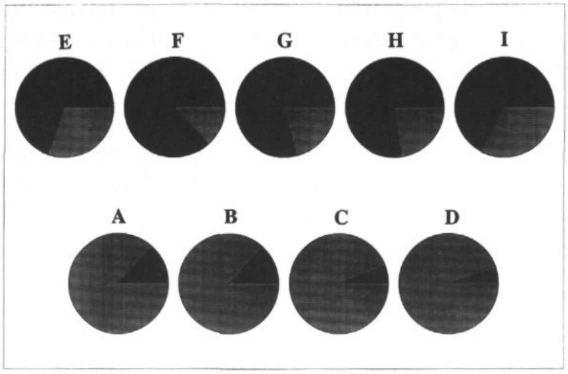

Figure 2. Pie charts for the total tracking duration for each of the nine saithe studied. Time spent at cage site A (black) is shown in comparison with time spent elsewhere (hatched).

In general, the fish displayed two different patterns of movement. Figure 2 shows the time spent at cage site A compared with time spent elsewhere for each fish. Five of the tagged saithe (fish E, F, G, H, and I) had a home range with a core area at the cages while four fish (A, B, C, and D) spent most of their time in deeper water to the east of the hydrophone array. The areas occupied by the two groups of fish are represented in Figure 3.

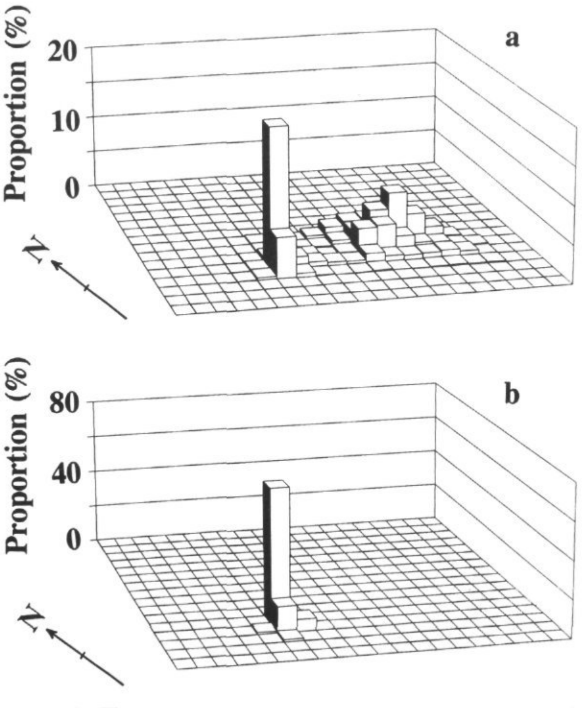

Figure 3. The areas occupied by the two groups of tagged saithe shown as the proportion of the total number of position fixes (one minute means) within 50 × 50 m squares. Note that for clarity the vertical scales are different to accentuate the data presented in (a). (a) Group one (saithe A, B, C, and D); (b) group two (saithe E, F, G, H, and I).

Both groups were less active at night and both demonstrated an increase in swimming activity coinciding with dawn. The fish that tended to remain at cage site A overnight often visited the adjacent cage site B (350 m away) at dawn. The fish with a core area in deeper water usually visited the cages at site A on a daily basis. Composite data showing the time spent in association with cage A for the two groups of fish in relation to time of day are presented in Figure 4.

Fish D (which had a depth tag) was only tracked for 16.6 h before the signal was lost, but within 2 h of release the fish reached a maximum depth of 70 m. When the fish briefly returned to cage site A the next morning, the swimming depth varied between 20 and 30 m.

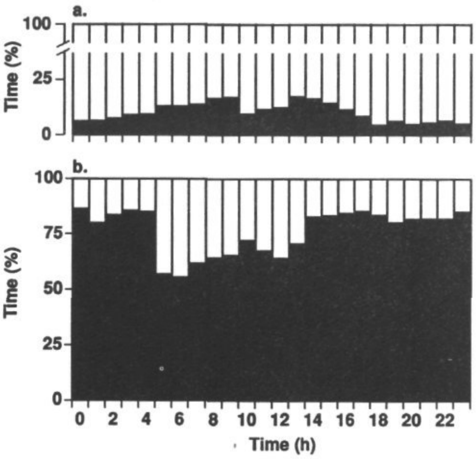

Figure 4. The mean time (hourly means for the duration of the tracking period) spent at cage site A (black) in relation to time of day for: (a) group one (saithe A, B, C, and D); (b) group two (saithe E, F, G, H, and I).

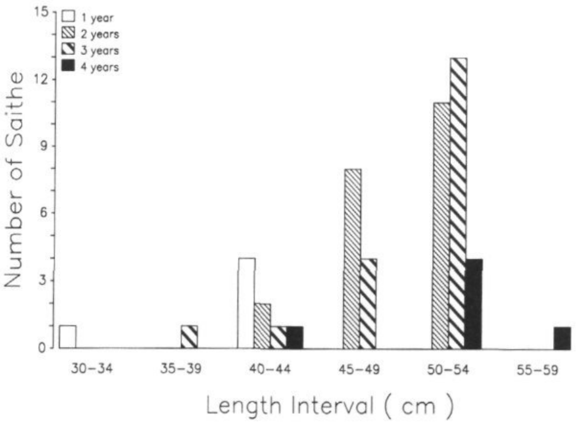

Figure 5. The age and length distribution of the saithe sampled from cage site A at the end of the study (n = 51).

Fish length in relation to age for the saithe sampled at the end of the study is shown in Figure 5. Thirty of the sampled fish were females and most of the fish were immature (38) or maturing (8). Examination of the stomach contents showed that most of the fish (34) contained food pellets only, while fourteen fish contained other additional food items.

Discussion

Traditional tagging has shown that wild saithe can stay around fish farm cages from one to seven months before offshore migration (Bjordal and Skar, 1992 and unpublished data). In the present study the emphasis was to obtain information on the daily local movements of saithe in relation to fish farms. Although individual saithe were tracked during this study, tagged fish were seen to swim and feed within shoals of others. These observations confirm that the behaviour described is representative of the movements of groups of fish.

Two distinct movement patterns were determined for the tagged saithe. Group one (fish A, B, C, and D) spent only brief periods of time in association with cage site A. Group two (fish E, F, G, H, and I) had a core area centred at site A and occasionally made brief excursions to the adjacent cage site B during the day. This behaviour is similar to that reported by Johnstone *et al.* (1991), who describe the movements of saithe in association with a natural reef. The reef formed the core area of their home range, and tagged saithe only swam away from the reef during the day. The observed pattern of regular movements between adjacent cage sites clearly indicates that saithe might be a possible vector for pathogens between fish farms.

Group one, which only occasionally visited cage site A, had a core area in the deeper water to the east of the array associated with a reef or underwater cliff. This area is a locally known saithe fishing location. It is well known by fishermen that saithe tend to accumulate around such features, which are termed "seiegrunner" (saithe reefs) in Norway.

Although saithe D (which bore a depth tag) was tracked for a relatively short period it is interesting to note that the fish did make a return excursion to cage site A 15.6 h after tagging. The fish appeared to follow the depth contours of the terrain and this may be indicative of the depth at which the saithe move between these locations. Further observations with depth transmitters may allow this observation to be confirmed in the future.

Fish aggregation devices (FADs) are an established method for enhancing the commercial exploitation of pelagic fish in the Pacific Ocean (Buckley *et al.*, 1989). Investigation of the movements and residence times of fish in relation to FADs has been described by Brill *et al.* (1984) using an acoustic tracking technique. As this study shows, fish farms act as aggregation devices for wild fish, both fish that may reside at the cages over a certain period of time and fish that visit the farm on a regular basis. This behaviour provides an ideal opportunity for cost-effective capture of wild fish, either at fish farms or at specially constructed traps ("inshore FADs") utilizing similar principles of fish attraction.

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Underwater noise radiated by research vessels

R. B. Mitson

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Levels of radiated noise from ships are such that many fish species are capable of detecting them at long ranges. A ship's noise field is extremely dynamic in terms of discrete frequencies and overall level, and the variation from vessel to vessel is great. The relationship between this noise field and any reaction by fish may be complex, but currently there are insufficient data to correlate specific observations with noise characteristics of the vessels causing the reaction. A selection of data on six research vessels is presented to illustrate the levels of variability encountered under a variety of running and working conditions. An outline is given of the noise measurements required if the problem of fish reaction to noise is to be solved.

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Introduction

Adverse effects of ship-radiated noise on fish behaviour have been noted by many authors but there is no clear picture of cause and effect. Fish can detect noise, often at considerable distances. The reason for a specific reaction, which can affect the availability of fish in the vicinity of a trawl, or along the track of an acoustic survey, can be related neither to the pressure level nor to the frequency spectrum of the noise. Many separate pieces of valuable knowledge exist, but for a variety of reasons they are not easily linked together, for example when observations on fish reaction to ship noise do not include a description of the vessel noise, usually because this is not known.

Interest in this subject is currently being revived because greater precision is sought in the assessment of fish stocks, whether by acoustic or by trawling methods, or a combination of the two. Low levels of high-frequency ship-radiated noise are necessary if the recent significant increase in the dynamic range of echo sounders (Bodholt *et al.*, 1989) is to be fully exploited.

An adequate description of underwater radiated noise can only be obtained by measurement under a variety of conditions. This is because of the extreme variability of the frequency spectrum and sound pressure levels in relation to speed, load, pitch angle of propeller, and age of vessel. It is timely to examine available noise data so the information in this paper has been collated from several sources, including the "grey" literature. It serves to emphasize the need for collection of data in greater detail if the questions of fish response and reaction are to be answered.

Fish hearing

Fish hearing varies from species to species so it is likely that there may be different reactions according to: (a) the noise frequency spectrum radiated from vessels; (b) the pressure levels; (c) a combination of the two; (d) the circumstances under which the noise is detected.

Under (d) we might expect complications due to other sensory effects, perhaps lights on a vessel at night, or its shadow during the day and possibly other factors such as seasonal effects. Studies to determine the sensitivity of fish to sound include Buerkle (1967, 1968), Enger (1967), Chapman (1964), Chapman and Hawkins (1969), Chapman and Sand (1974), and a recent review by MacLennan and Simmonds (1992). Figure 1 shows the hearing thresholds for several species of fish taken from some of these sources. Of these fish, herring have the most sensitive hearing and also the broadest frequency response. Other species show a sharper cut-off immediately following their most sensitive hearing region.

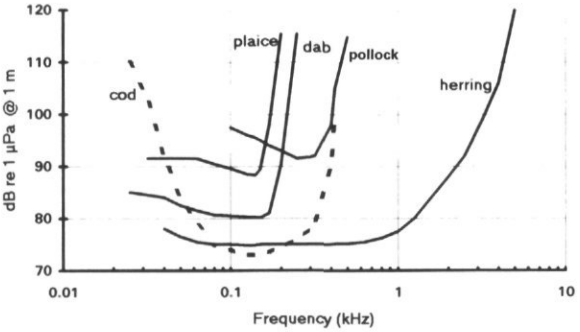

Figure 1. Audiograms of fish hearing sensitivity for cod (Buerkle, 1967); plaice and dab (Chapman and Sand, 1974); herring (Enger, 1967); pollock (Chapman and Hawkins, 1969).

Noise detection and reaction by fish

The audiograms in Figure 1 enable the calculation of distances at which the fish can detect noise (Buerkle, 1977; taking into account possible masking effects of the ambient level, Buerkle, 1969) but give no direct clue as to the specific stimulus to which they will respond. Evidence suggests a large difference between the distance at which fish detect sounds and the distance at which they react.

Olsen (1976) observed directional response in herring (*Clupea harengus*) at more than 80 m and Sorokin *et al.* (1988) showed that Pacific sardine (*Sardinops sagax melanostica*) had the ability to determine the direction of a 60 Hz pulsed source at up to 150 m. Ona (1988) detected diving reactions in cod (*Gadus morhua*) 200 m in front of a vessel moving at 3 knots, the fish spreading horizontally and vertically, but at 10 knots the reaction was less. Assuming a controllable pitch propeller (CPP), a possible explanation is that the overall noise level in the hearing band of the fish was less at 10 knots because cavitation often decreases slightly with speed for a CPP. Alternatively, a strong tone or tones may have caused a reaction at low speed but have been swamped by cavitation above 3 knots. In this report and another using the same vessel (Ona and Chruickshank, 1986), the propeller was deemed to be the major cause of disturbance to the fish. Without more details of the vessel, or its propeller, it is difficult to speculate; a singing propeller producing a discrete tone seems likely, but even the whine from a gearbox can be radiated into the water. Propeller-induced vibration of the hull can cause very high levels of low-frequency noise.

Engås *et al.* (1991) observed the reaction of acoustically tagged cod to an approaching research vessel by tracking the detailed movements of individual fish; their results appear to confirm that the fish could sense the bearing of the vessel as it approached. These authors remind us that there is a directional pattern to ship-radiated noise, which in this instance may have had a herding effect when the fish sought minimum intensity of the noise field.

From the evidence put forward by Ona, and Ona and Chruickshank, using a 60 m, 1000 HP vessel and by Engås *et al.* with a 30 m ship of 165 HP, cod and haddock perceived noise from these vessels and reacted to it. The effect of the larger vessel appeared to be threatening at a range of about 200 m and fish made immediate movements towards a noise field of lower intensity, moving horizontally and vertically. At the same range the small ship caused the fish to "swim calmly along in front of the vessel". Around 100 m the swimming pattern became restless until the fish suddenly increased its swimming speed, giving a rapid diagonal burst forward and out of the track of the vessel. Taking a simplistic view we might consider a 25 Hz tone of 160 dB for the big vessel. At 200 m this is likely to be reduced to 114 dB, ≈15 dB above the hearing threshold. The ratio of engine power of the two ships is about 16 dB, so the level of a similar tone from the small ship might be 144 dB, which at 200 m is

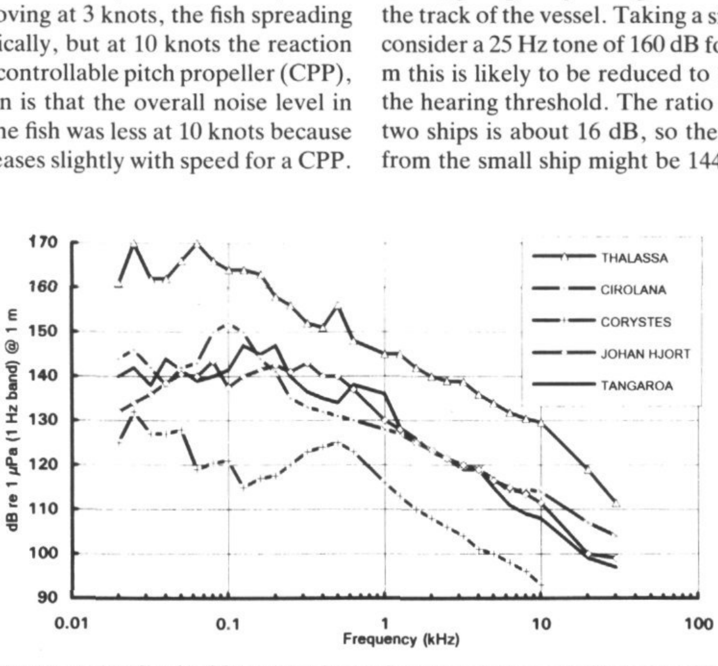

Figure 2. The noise spectrum pressure levels of five research vessels at a nominal speed of 11 knots with curves averaged over one-third octaves. Three of the vessels, "Thalassa", "Johan Hjort", and "Tangaroa", have controllable-pitch propellers whose noise level can change markedly for constant ship speed but with different pitch of the blades and/or the shaft speed.

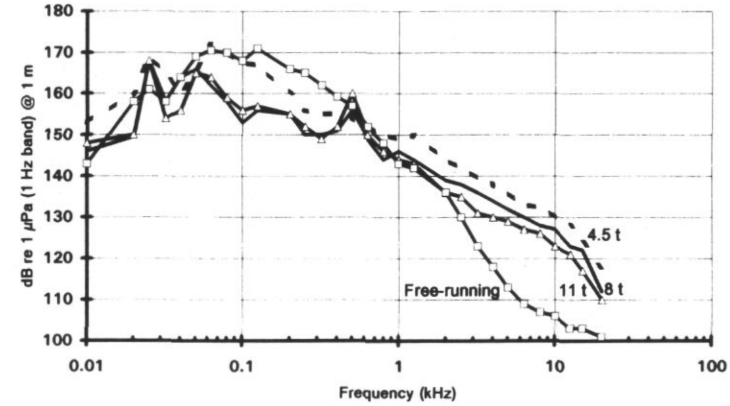

Figure 3. This is of special interest because FRV "Thalassa" is loaded as if trawling. All four runs were at 3 to 4 knots. Between 10 Hz and 100 Hz there is a complex interchange of levels for the different conditions. From 100 Hz to 1 kHz a clearer pattern is seen with the free-running state producing most noise. This is reversed at frequencies above 1 kHz where the lightest of loaded conditions makes most noise.

reduced to 98 dB, rather close to the hearing threshold. At 100 m it will be 104 dB and readily detected.

Radiated noise levels

A band of pressure levels against frequency was proposed wherein the noise signatures of fishery research vessels should be contained (Mitson, 1989). This implied that no tonal levels should exceed the top line of the graph shown in the paper. More detail is given in Mitson (1991) where the importance of narrowband measurements is also stressed. Normal presentation of radiated noise levels is *referred* to a 1 Hz bandwidth but shown in an averaged form because of the difficulty of displaying narrowband levels over four decades of frequency. The smoothing effect of averaging can disguise very strong tones present in the true signature occurring within the hearing spectrum of fish. Figure 2 compares several research vessel signatures at a nominal free-running speed of 11 knots (+0.5, −1), typical for acoustic surveys. It becomes clear that this type of graph has limited significance when the following data are examined. The vessels are discussed in turn below.

FRV "Thalassa"

After being re-engined in 1984 there was a significant drop in catches of certain fish species (see Sparholt, 1990), so in 1991 a noise ranging trial was carried out. FRV "Thalassa" noise levels are typically 20 dB greater than the next three vessels on the graph. Peaks represent regions where line frequencies (tones) have sufficiently high levels to raise the overall noise level. For some of these the amplitude is known, e.g. the tone at 25 Hz has a peak of 174 dB, and another at 480 Hz is 176 dB, 4 dB and 20 dB above the mean levels, respectively. Diner and Masse (1987) made many observations of fish behaviour with the vessel's omni-directional sonar and found 200 m was a typical range for fish schools to take avoidance action.

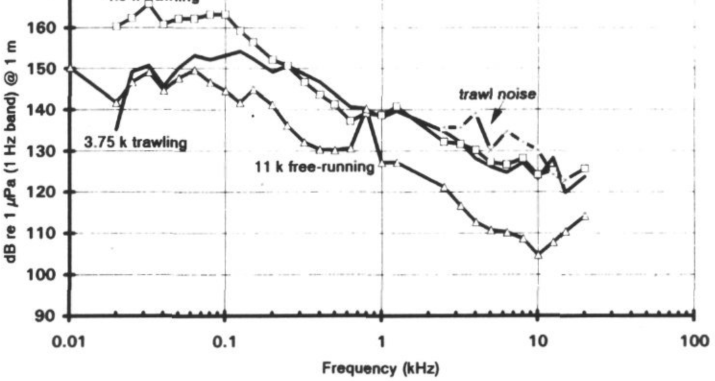

Figure 4. Noise levels for FRV "Explorer" when towing a bottom trawl at two speeds; also the level for a free-running state at 11 knots. Note the large increase in noise, when trawling, between 10 Hz and 120 Hz for a difference in speed of about 1 knot. Noise from the trawl is dominant from about 2 kHz to 10 kHz.

A series of measurements was made when "Thalassa" simulated trawling conditions by towing a loaded barge on the surface. Figure 3 shows four graphs with the vessel moving at speeds of between 3 and 4 knots, each representing a different operating condition, i.e., free-running, then loads of 4.5, 8, and 11 tonnes. Considering these in turn: (a) Free-running: peaks are evident within the band of fish hearing but are not pronounced. The noise falls off sharply beyond 1 kHz. (b) 4.5 tonne load: peaks at 25 and 65 Hz are high but the rest of the spectrum falls away fairly smoothly, albeit at a higher level than any of the other conditions. (c) 8 tonne load: the 25 Hz peak is of a similar level to (b) but sharper, with a rise in the spectrum at 50 Hz but the peak at 65 Hz has disappeared. Another is seen at 480 Hz after which the spectrum falls away with a similar but lower slope to (b). (d) 11 tonne load: here the 25 Hz peak is identical to (c), there is a rise centred at 55 Hz and the peak at 480 Hz becomes very prominent, thereafter the slope is lower than (c).

The increase in high-frequency noise level during the simulated trawling appears to be related to the propeller pitch which was set at 6, 10, and 13 degrees for the loads of 4.5, 8, and 11 tonnes, respectively.

FRV "Explorer"

This steam-powered vessel radiated a high level of underwater noise. When in free-running mode the propeller "sang" at 830 Hz, hence the marked peak at that frequency in Figure 4. The noise ranging included some runs when towing an Aberdeen bottom trawl at different speeds, as shown in Figure 4. These results show a distinct contrast with the FRV "Thalassa", where a loaded barge was towed on the surface to simulate a trawl. This produced an increase in high-frequency noise but a decrease at low frequencies. In Figure 4 it is clear that "Explorer" produced a very significant 10–20 dB increase in low-frequency noise (20 to 150 Hz) for just over 1 knot increase in towing speed. Another feature of Figure 4 is that the propeller singing tone, clearly seen at 11 knots, is lost in the increased cavitation level due to the loading effect of the trawl on the vessel. Noise was recorded from the trawl as it passed close to the hydrophone but at 3.75 knots it was not distinguishable from the vessel noise. At 4.9 knots the trawl noise was distinctive in the band 700 Hz to just over 10 kHz.

FRV "Johan Hjort"

Over much of the frequency range for the speed of 11 knots this modern diesel-engined vessel has a lower noise level than FRV "Explorer". No special noise-reduction features were incorporated but the low-frequency levels of 20–40 Hz are particularly low at 11 knots. As with all CP propellers, noise levels can alter dramatically for a slight alteration of blade pitch and shaft rate although the resulting change in ship speed may be small. In Figure 5, at 10 Hz and 65 Hz, there is an increase of 20 dB for a 0.5 knot *reduction* in speed. Narrowband analyses are not available so the frequency and intensity of discrete tones giving rise to the increase are not known.

FRV "Cirolana"

Experimental noise reduction methods were used when this vessel was built in 1970. At 11 knots the underwater radiated noise signature is raised significantly by a high level centred on 100 Hz; for lower frequencies the noise-reduction measures were effective but the lack of a noise-reduced propeller gives about average results at high frequencies. Moving mechanical parts become worn as vessels age and the levels of noise and vibration might be expected to increase. There is a lack of noise-ranging reports taken throughout the life of vessels to

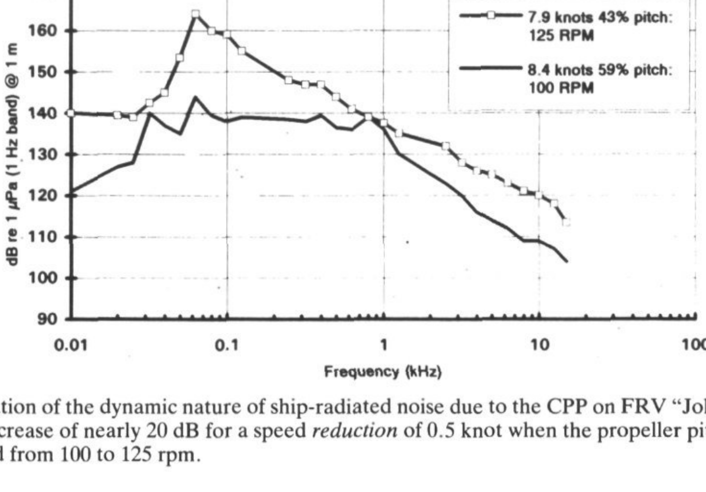

Figure 5. A clear indication of the dynamic nature of ship-radiated noise due to the CPP on FRV "Johan Hjort". At about 10 Hz and 60 Hz there is an increase of nearly 20 dB for a speed *reduction* of 0.5 knot when the propeller pitch is changed from 59% to 43% and the shaft speed from 100 to 125 rpm.

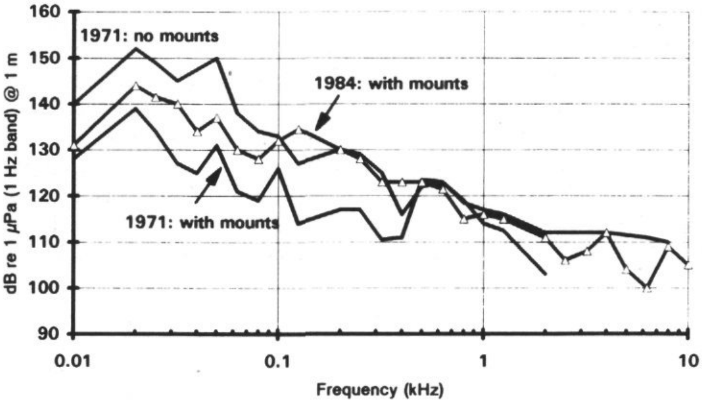

Figure 6. Noise levels for FRV "Cirolana" at two operational states and a comparison of levels after 13 years in service, all at 6 knots. An unusual form of construction allowed measurements with the engine resiliently ("with mounts") or solidly mounted. High frequencies are dominated by propeller cavitation.

allow comparison of the noise signatures over a number of years. FRV "Cirolana" was ranged in 1971, soon after coming into service and again in 1984. Because of differences in recorded speed of the vessel between the two noise rangings the most valid comparison is at 6 knots (Figure 6). There are two data series for 1971, one with the engine raft resiliently mounted, giving significantly lower levels than when it is solidly mounted. The flexibility of the design allowed changing from one state to the other in a few minutes. By 1984 the low-frequency noise level had increased by about 10–20 dB between 30 Hz and 4 kHz but was less than the level when solidly mounted in 1971. This may indicate an increase in engine noise and lower efficiency in the mounting. Above 500 Hz to 2 kHz there is little change but the peak at 4 kHz and another at 7 kHz may have resulted from a change of propeller in the interim period.

FRV "Tangaroa"

The overall level at 11 knots is similar to FRV "Johan Hjort" and FRV "Cirolana" but there are more peaks in the low frequencies, indicating high-level tones. In the absence of complete narrowband data these peaks cannot be classified precisely. From limited narrowband data available (not contained in this paper) it is clear that the propeller "sings" at 825 Hz with a level that varies up to a maximum of 164 dB, according to the rpm and pitch of the blades. Cavitation is quite severe and is present at most operating speeds; in common with CPPs it tends to decrease slightly at higher rpm, i.e. the performance is worse at slower speeds.

FRV "Corystes"

Comprehensive noise-reduction measures were taken to meet the specification at 11 knots. Although the aim was lower, the maximum acceptable overall level was 150–10 log $F_{Hz.}$. At frequencies above 10 kHz the maximum level was set on the basis of single fish detection in shallow water against reflected noise. Below 1 kHz it was largely determined by the requirement for low internal noise levels and a desire to avoid scaring fish. Apart from a minor excursion between 400 and 800 Hz the results were good and well below the maximum acceptable level.

During the first series of trials a number of problems occurred which were later rectified and are detailed in Kay *et al.* (1991). Two, though, warrant a brief mention here. The first concerns a strong tone at 300 Hz, about 33 dB above the general level, due to ripple on the electrical supply to the propulsion motors at six times the supply frequency, resulting in a vibration at that frequency which was transmitted into the water. As this was within the hearing range of some fish species, it was necessary to reduce this to the general noise level, and chokes were fitted in the circuit of each propulsion motor. These chokes can be switched in and out of circuit and an experiment has been conducted to judge their effect during bottom trawling (Nicholson *et al.*, 1992). The second problem was an unexpected increase in the level above 500 Hz when even a fraction of helm was applied. An intense, piercing squeal was emitted, owing to the rudder bearing being too tight. This might well have had a scaring effect on some species of fish.

Noise ranging of research vessels

Current methods of assessing and comparing noise levels are not fully adequate for fishery research vessels. The facilities designed for naval purposes are excellent in themselves, with standardized techniques and procedures common to many parts of the world. Difficulties arise when measurements of a trawler in action are necessary, because the bottom-mounted hydrophones are normally close to one another and on the course of the vessel. Risk of damage by towing a trawl through the hydrophone configuration is too great to allow such an exercise, so few results are available for vessels in a loaded or trawling condition. This is unfortunate because the free-running results are normally quite different, as seen in the examples above. The pattern to the radiated noise in the horizontal plane is difficult to measure, but for the future such a method needs to be devised. This should be part of the noise-ranging procedure, which at present takes a measurement on either side of the vessel but the results are often combined.

Discussion

Fish can detect noise from considerable distances but their reaction, if any, to a vessel cannot yet be linked to any particular aspect of ship-radiated noise. The extreme variability of the noise frequency spectrum and levels for six fishery research vessels has been demonstrated at different speeds and loadings where data are available. It is clear from the figures that there is a need to obtain a wider variety of measurements on all vessels than is the present practice. With such information it should be possible to devise and run experiments to determine what stimuli cause fish to react. The benefits would be twofold. First, operational procedures when trawling or surveying acoustically could be modified to cause the least disturbance to fish and the instrumentation. Second, it would be possible to provide a shipbuilding specification for the minimum effective noise reduction, thus keeping costs low.

Acknowledgements

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III. APPLICATION OF FISH BEHAVIOUR KNOWLEDGE

ICES mar. Sci. Symp., 196: 155–160. 1993

Fish-herding effect of an air bubble curtain and its application to set-net fisheries

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Arimoto, T., Akiyama, S., Kikuya, K., and Kobayashi, H. 1993. Fish-herding effect of an air bubble curtain and its application to set-net fisheries. – ICES mar. Sci. Symp., 196: 155–160.

In order to develop a new operating system for set-net fisheries, the herding effect of an air bubble curtain was studied in laboratory and field experiments. The response of fish to a moving air bubble curtain was examined in an annular tank while air flow and speed of movement were varied. The fish continued swimming to avoid the approaching curtain. For practical application to a set-net operation, several air tubes were set at intervals on the bottom, and the bubbling position was switched among them in a sequence. The fish reaction was similar to that to the moving curtain; swimming speed and direction could be controlled by the valve switching operation. In a field experiment, conducted with a full-size chamber trap to confirm the application of the methods, the fish were successfully herded to the final capture area by sequencing the bubbling position. In a set-net with a final chamber trap, the fish were forced to enter through the non-return device of the slowly tapering funnel. This system can help to save time and labour during net-hauling, as well as in designing an automated capture system by continuous accumulation of fish in the non-return trap.

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Introduction

Control of fish behaviour by an air bubble curtain was first reported by Smith (1957, 1961). In the succeeding three decades, its barrier effect has been examined from various points of view for purposes of capturing and controlling fish (e.g., Imamura and Ogura, 1959; Igarashi, 1963; Kuznetsov, 1971; Lieberman and Muessig, 1978; Stewart, 1981; Patrick *et al.*, 1985 and Sager *et al.*, 1987).

We investigated the fish-herding effect of an air bubble curtain both in the laboratory and in field experiments, with the aim of its practical application to set-net fishing operations.

Laboratory experiments

The first step in our experiments was the basic confirmation of the herding effect of a moving air bubble curtain in a small tank (Fig. 1) (Akiyama *et al.*, 1991). An air pipe was set on the bottom of an annular trough, and rotated so as to create a moving barrier in the form of an air bubble curtain. The response of fish to the bubble curtain was observed in relation to variation of its moving speed (11–32 cm s^{-1}) and air flow rate (10–40 l min^{-1} per 1 m pipe length).

Jack mackerel (*Trachurus japonicus*) (88–113 mm TL), threeline grunt (*Parapristipoma trilineatum*) (161–187 mm TL), and Japanese parrotfish (*Oplegnathus*

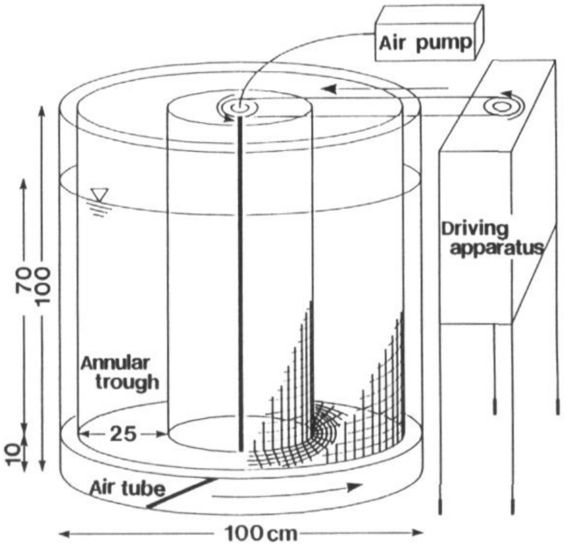

Figure 1. Experimental apparatus for small-scale tests of the fish-herding effect of an air bubble curtain. All dimensions are in cm.

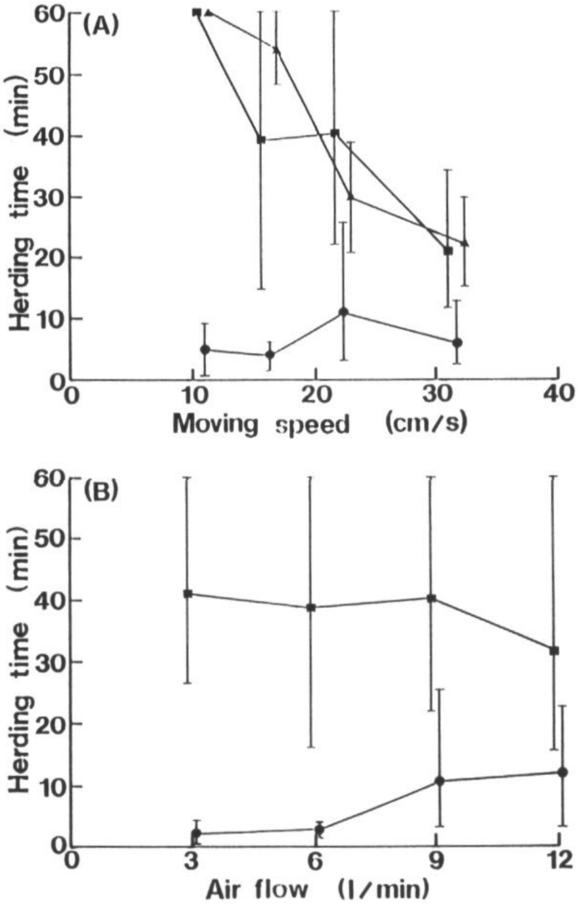

Figure 2. Variation of herding time in relation to (A) bubble curtain moving speed with constant air flow of 9 l min^{-1}, and (B) air-flow rate with constant bubble curtain speed of 22.5 cm s^{-1}. Vertical bars and symbols indicate range and average values for 9 trials of each of the following fish species: filled circles, Japanese parrotfish (*Oplegnathus fasciatus*); filled squares, jack mackerel (*Trachurus japonicus*); filled triangles, threeline grunt (*Parapristipoma trilineatum*) (grunt data are not available for graph (B)).

fasciatus) (101–128 mm TL) were used respectively in groups of three individuals. Each species was tested separately. Each species swam steadily, maintaining position just in front of an approaching bubble curtain. The herding effect was expressed as the time elapsed until one of the three individuals failed to keep its position and was left behind the curtain within a one hour observation period. The results are shown in Figure 2. In accordance with fish species and size, fish responses varied with experimental conditions. It is noteworthy that jack mackerel and threeline grunt kept swimming to avoid an approaching bubble curtain for the whole 60 min in all nine trials at the low herding speed of 11 cm s^{-1} (Fig. 2A). In general, the herding effect was shown more strongly by the pelagic species than by the coastal fish. The amount of air flow and the speed could be the determining factors for the successful effect of the air bubble curtain, even in the small closed experimental area.

Similar experiments were conducted in a larger-scale tank (Fig. 3) (Akiyama *et al.*, 1992). With a view to practical application to a set-net operation, 16 radial air tubes were set up at intervals on the bottom and the bubbling position was alternated in sequence. The response of a small school of 10 jack mackerel was examined in relation to variation of the bubbling interval from 1 to 10 s, which is equivalent to 7.9–79 cm s^{-1} (0.5–5.4 body lengths per second). In this experiment, an air flow rate of 50 l min^{-1} m^{-1}, which could create an opaque barrier in the tank, was employed. The fish reaction was similar to that to the moving curtain in a smaller tank, with the swimming speed and direction being controlled by the valve switching operation.

The results are shown in Figure 4. At lower air curtain speeds (10–30 cm s^{-1}), the fish swimming was not stable, so the average swimming position was far ahead of the bubbling position. In experiments with speeds faster than the cruising speed of 35.5 cm s^{-1} (observed during voluntary swimming in the tank), the typical escape reaction was obtained: fish maintained a steady swimming performance as a school 1–3 m ahead of the bubbling. Here, in the night-time experiment with ambient luminance lower than 0.1 lux, the tendency of fish reaction was similar to that in daytime.

When an annular trough was blocked by a netting panel or an air bubble curtain, fish were successfully herded toward the stationary barrier by sequencing the bubbling position. In this way fish were confined and concentrated between the approaching bubble curtain and the stationary barrier.

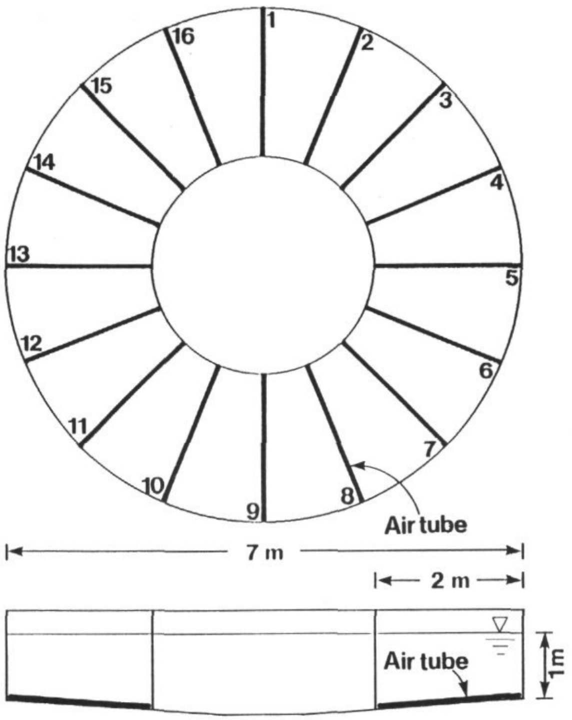

Figure 3. Experimental arrangement of an annular trough with 16 radial air tubes arrayed on the bottom at uniform intervals. The bubbling position was alternated in sequence at different time intervals of 1, 2, 3, 5, and 10 s to control the herding speed. The response of a school of 10 jack mackerel (*Trachurus japonicus*) to the rotating air bubble curtain was observed and recorded as the number of sections between the fish and the bubbling position for each bubbling instance during 10 complete rotations of the air bubble curtain through the trough. Air flow rate was 50 $l\ min^{-1}\ m^{-1}$.

Field experiments

Three different trials were conducted with model and practical set-nets. The experimental conditions are listed in Table 1. The first trial was conducted in a small-scale set-net to drive the fish toward the capture area in the chamber trap, which measured 33 m long, 24 m wide, and 18 m deep. The experimental arrangement is shown in Figure 5. The air tube (17 mm dia.) made of 20 m long porous rubber was set on the bottom of the chamber trap which was located just below an entrance funnel. Air was supplied from two sets of air tanks (50 l, 150 kgf/cm^2) on board a small fishing boat (8.0 m long, 2.0 G/T) moored at the far end of the chamber trap. The air tube was towed at a speed of 1 m min^{-1} by pulling the high-pressure hose connected to the air tank. The air curtain and fish behaviour to it were observed by divers and recorded by an underwater TV camera. Experiments were conducted with air pressure varying from 3 to 5 kgf/cm^2.

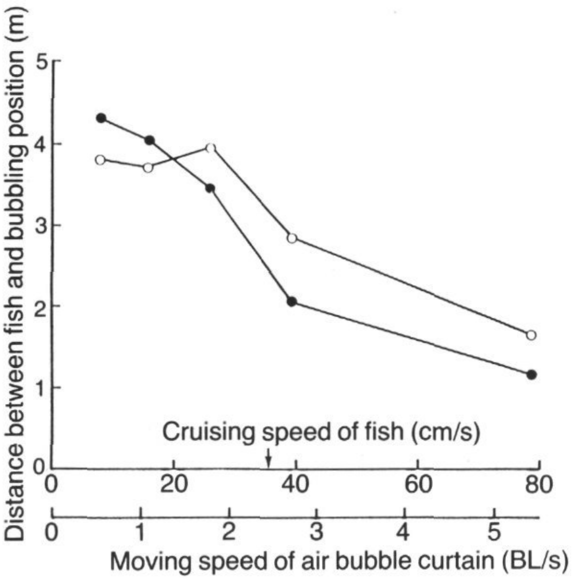

Figure 4. Average distance between a school of 10 jack mackerel (*Trachurus japonicus*) and bubbling position, in relation to the calibrated moving speed of an air bubble curtain in day (open circles) and night (filled circles) experiments. Circles indicate the average value for five replicate trials in each condition. The normal cruising speed of these fish was defined as 35.5 cm s^{-1} based upon voluntary movement in an annular trough. For further details, see text.

In the chamber trap, several fish species could be identified, such as jack mackerel (*Trachurus japonicus*), king fish (*Caranx equula*), ribbon fish (*Trichiurus lepturus*), and Japanese anchovy (*Engraulis japonicus*).

The air bubble curtain created a perfect visual barrier at higher air pressures of 4–5 kgf/cm^2. At 3 kgf/cm^2, air ejection was inadequate to create an ideal barrier throughout the length of the air tube on the bottom at 18 m depth. Long-distance underwater observation inside the chamber trap was limited, owing to poor visibility and the muddy cloud generated by air ejection and the towed tube. Short-range observations revealed that fish schools which encountered the air bubble curtain, avoided it, and were driven to the capture end. When the air bubble curtain approached the final end, the fish were expected to be concentrated there. Most, however, could return to the entrance by passing through gaps between the air bubble curtain and the side wall netting. It is noteworthy that no fish passed through the air bubble curtain as observed by the limited short-range view.

In the second stage of the experiment, the response of fish to the air bubble curtain was observed in a full-scale model of a set-net, which consisted of a main net and a final trap with narrow tapered funnel (Fig. 6). Bubbling positions were switched to herd the fish through the funnel toward the final trap. Sufficient air flow was obtained with an air compressor of 870 l min^{-1} and

Table 1. Experimental conditions used in the field test of the fish-herding effect.

Exp. no.	No. 1	No. 2	No. 3
Location	Takanoshima fishing ground in Chiba Prefecture	Kaiso fishing port in Ishikawa Prefecture	Matsuzaki fishing ground in Shizuoka Prefecture
Date	Oct 1990–Mar 1991	Jun 1991	Nov 1991
Net scale	33 m long × 24 m wide chamber trap	28 m long × 10 m wide full-scale model net	120 m long × 21 m wide set-net
Specification of air tube			
Material	Porous rubber	PVC	Nylon
Diameter (mm)	17	16	15
Length (m)	10/20	5–10	16–30
Numbers	1	8	19
Set interval (m)	–	3	4–6
Hole diameter (mm)	–	0.5	0.75–1.0
Hole interval (cm)	–	10	15–30
Air supply	Air tank	Compressor	Compressor
Specification	50 l, 150 kgf/cm^2	15 ps/3600 rpm	50 ps/3000 rpm
Air flow (l min^{-1})	380	Max. 870	Max. 5000
Pressure (kgf/cm^2)	3–5	Max. 10	Max. 7
Fish species	Jack mackerel (*Trachurus japonicus*) King fish (*Caranx equula*) Ribbon fish (*Trichiurus lepturus*)	Jack mackerel (*Trachurus japonicus*) File fish (*Navodon modestus*) Yellowtail (*Seriola quinqueradiata*)	Jack mackerel (*Trachurus japonicus*) Frigate mackerel (*Auxis thazard*)

10 kgf/cm^2 at maximum, for a bottom depth of 10 m. About 100 fish of several species, such as yellowtail *Seriola quinqueradiata*, filefish *Navodon modestus*, and jack mackerel *Trachurus japonicus*, were introduced into the main net and adapted for 1 day or more prior to the experiment. Underwater observations and successive net-hauling of the final trap showed that the fish in the main net were successfully herded to the final trap by switching the bubbling position in sequence from the first tube to the end of the funnel. Some species such as jack mackerel showed hesitation in approaching the narrow funnel, and sometimes retained their position even when the bubbling position approached, so that they were left behind when the bubbling position passed them.

As the third stage, a practical experiment was con-

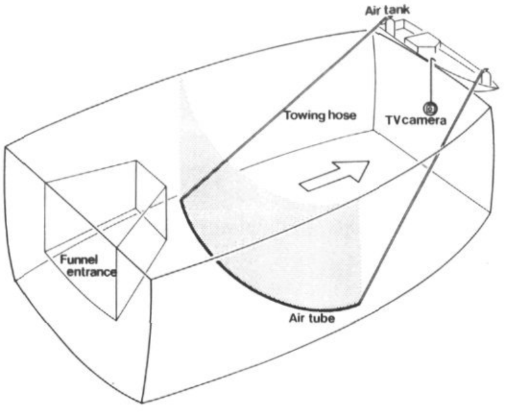

Figure 5. Experimental arrangement for fish herding by a towed air bubble curtain in the chamber trap of a set-net 33 m long, 24 m wide, and 18 m deep, with a funnel entrance from a main net.

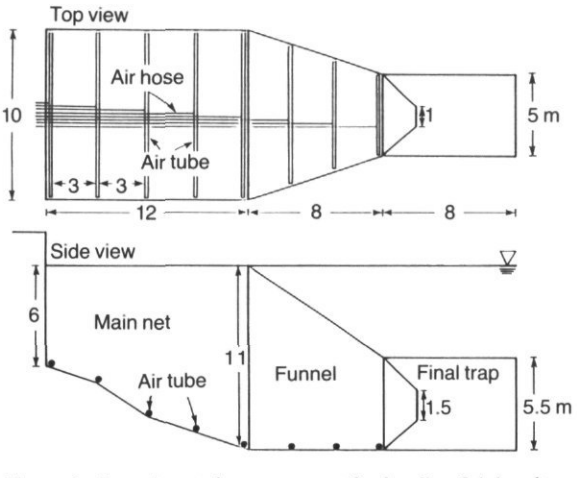

Figure 6. Experimental arrangement for herding fish by alternating the position of an air bubble curtain in a full-scale model set-net. All dimensions are in m.

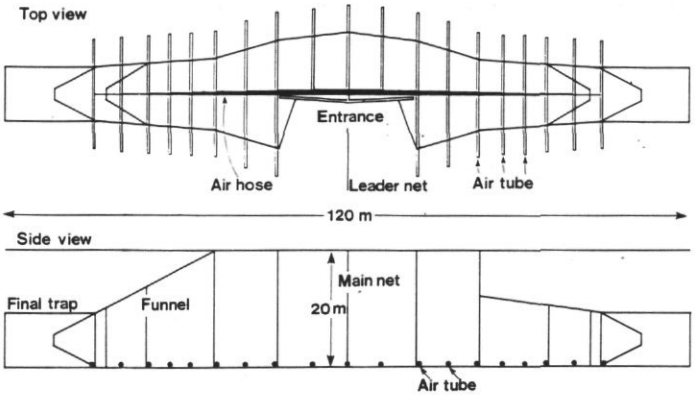

Figure 7. Experimental arrangement for herding fish by alternating the position of an air bubble curtain from the centre to the final trap in a set-net.

ducted in a small-scale set-net 120 m long and 20 m deep. The arrangement of the net and the air tubes is shown in Figure 7. The set-net was a demersal type with double final traps located at opposite ends of the main net. The procedure for herding the fish inside the main net was first to intercept the entrance mouth, and then to alternate two lines of bubbling position in sequence from the centre to the ends, toward each final trap. An air compressor capable of supplying 5000 $l\ min^{-1}$ was employed. The creation of the air bubble curtain and its manual position alternation were satisfactory. The herding effect was observed and video-recorded by divers for schools of jack mackerel and frigate mackerel (*Auxis thazard*). The problem, however, was still encountered that fish hesitated to enter the narrow tapered funnel and tended to remain in position.

We are taking these practical experiments to the final stage to confirm the herding effect of an air bubble curtain by comparing the daily catch amount with and without this herding procedure.

Discussion

The set-net fishery is one of the principal methods of coastal fishing in Japan. It is classified as passive stationary gear consisting of a barrier system (a leader net) and a multiple trapping system (non-return devices with funnel entrance). The leader net intercepts the migration of fish schools and guides them into the main net (von Brandt, 1984). The best designs of non-return entrances and funnels have been investigated (Nomura, 1980). It should be emphasized, however, that not all fish in the main net enter the trap net. This means that the majority of fish can readily escape the main net through the entrance (Inoue and Arimoto, 1988).

To harvest the fish from the trap, net-hauling is conducted every morning, and sometimes twice a day during the best fishing season by also hauling during the evening. The operational procedure is principally manual, with the aid of machines such as net-haulers or capstans for rope hauling (Miyamoto, 1971; Honda, 1976). Air lifting systems have already been developed with the air hose bag set under the chamber trap (Fukahori *et al.*, 1988). Although such mechanization can save time and labour during net hauling, the principle of the operation remains unchanged.

The results of our experiments suggest an application of the air bubble curtain to set-net fishing operation, by herding fish toward the capture area without drying up the bottom net of the chamber trap. This kind of fish-herding system can promise the additional advantage of establishing an innovative fishing method: an automated capture system by continuous accumulation of fish from the main net into the non-return trap of a set-net. This might be done with the aid of timer-controlled operation for air valve switching, and remote control with a sensing system for fish detection. For this purpose, further practical experiments will be required, especially towards designing non-return devices for preventing the escape of fish from the final trap. Final traps can then be alternated to act as keeping cages, which may lead to a stable situation of harvesting and marketing in set-net fisheries.

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Selective flatfish trawling

Bjarti Thomsen

Thomsen, B. 1993. Selective flatfish trawling. – ICES mar. Sci. Symp., 196: 161–164.

In flatfish trawling within the 12-mile baseline around the Faroe Islands, large amounts of roundfish (cod) have been caught. Differences in behaviour of fish species (cod, flatfish) described in the literature prompted ideas to modify an existing trawl to reduce the catch of roundfish while retaining flatfish. Model trials were used to verify the shape of the modified trawl, and underwater video was used to test and make final adjustments on the full-scale trawl. Removing the front part of the upper panel and using large meshes (holes) in a part of the upper batings panel allowed cod to escape from the trawl. Commercial comparative fishing has shown that these changes can reduce the catch of cod by 38% without loss of flatfish.

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Introduction

When trawl fishing was banned within the 12-mile baseline around the Faroe Islands in 1964, a number of fish species were left underexploited. Therefore a licence fishery for small trawlers inside the 12-mile zone has been allowed since 1971. The intended target species in this fishery are lemon sole (*Microstomus kitt* Walb.), plaice (*Pleuronectes platessa* L.), monkfish (*Lophius piscatorius* L.) and catfish (*Anarhichas lupus* L.); nevertheless more than half the catch has been roundfish, mostly cod (*Gadus morhua* L.), a lesser amount of haddock (*Melanogrammus aeglefinus* L.) and occasionally saithe (*Pollachius virens* L.). Severe overfishing of cod in recent years has brought into question the justification for this fishery. Restriction of the fishery to areas where the target species are most abundant has not produced satisfactory results. The legal mesh size in the area is 145 mm, but owing to the size of the lemon sole, a 120 mm mesh is allowed in the licence fishery, making the by-catch of cod a matter for more concern. Furthermore, flatfish can mask the meshes in the codend and prevent small fish from escaping (Main and Sangster, 1982).

Against a background of earlier work described in the literature, experiments to reduce the by-catch of roundfish were carried out in 1990. The aim was to make minor modifications to an existing trawl, rather than to introduce new trawling gear.

Literature

It has been known since the early days of trawling that a trawl does not filter fish out of the sea passively, but that there is a certain interaction between trawl and fish. Early work showed differences in trawl efficiency for different fish species with different trawl riggings (Bagenal, 1958), and that fish are affected in front of a trawl (Beamish, 1969), but not until diving techniques allowed direct observation of fish in trawls (Main and Sangster, 1981) was a more precise picture of fish reaction to trawls achieved. This knowledge can be used to make trawls more efficient and more selective, e.g. Wardle (1983) suggests using the different appearance of trawl objects to control fish reactions.

Main and Sangster (1981) described a typical rising behaviour of haddock when falling back into a trawl, while both cod and flatfish entered the trawl close to the lower panel. Difficulties in separating cod and flatfish in the front part of a trawl were also confirmed by trials with separator panels (Main and Sangster, 1982). On the other hand, trials with sorting panels back at the codend (Hillis and Carrol, 1988) indicated that cod may rise in the upper half of the trawl while flatfish remain in the lower part. Also, sorting devices in the middle of the trawl body (Sørensen and Yngvesson, 1987) indicate possibilities of separating roundfish from flatfish.

Square mesh in the codend will increase and decrease the selection size of roundfish and flatfish respectively

(Walsh *et al.*, 1989), but separation of roundfish and flatfish cannot be achieved by size selectivity only, and it is preferable for the selection to occur earlier in the catch process.

Materials and methods

The first part of the work was done during spring 1990 at the Danish Institute for Fishery, Technology, and Aquaculture (DIFTA), Hirtshals, Denmark, which has available a large collection of underwater videotapes on fish behaviour from different sources and a flume tank for model tests.

Based on expected fish reaction, it was believed that a modified trawl with the front part of the upper panel removed would avoid catch of haddock, and that very large meshes in the upper panel would allow cod and other roundfish to escape.

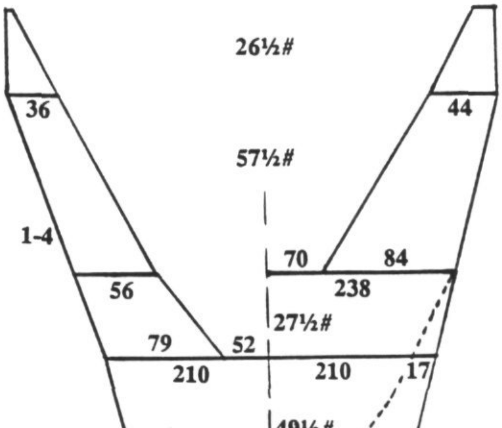

Figure 1. Drawing of the trawl used. Mesh size is 120 mm in the codend and 135 mm elsewhere. The new headline is indicated as a dotted line. Numbers are panel width and depth (#), expressed in meshes, and taper ratio (1–2).

A two-panel, 420 meshes (135 mm) trawl widely used in the licence fishery was taken as a basic model. Models scaled to 1:8 (Dickson, 1961), both of the basic trawl and of a modified trawl with headline lengthened to be about 7 m behind the groundgear, were tested in the flume tank to ensure that the modification did not lead to distortion of the trawl. The modified trawl showed good shape with mesh openings as in the traditional trawl. Figure 1 illustrates the basic model, with the new headline indicated, and Figure 2 depicts the two trawls as seen in the flume tank.

When the model worked satisfactorily, the second part of the experiment was conducted on fishing grounds in the Faroes in June/July 1990. A full-scale modified trawl was built and tested against a traditional trawl, using a licence trawler MS "Skardhamar" (47 brt, 480 hp). A towing speed of 2.2 knots was used throughout the experiment.

During the first 10 days an underwater video was used to monitor fish reaction to the modified trawl. This was done at 80–120 m depth using the remote controlled vehicle "Focus" (on hire from DIFTA). In particular the vertical distribution of cod and flatfish in different parts of the trawl was examined to find suitable places to introduce large meshes for cod to escape.

After underwater video confirmed the desired trawl performance, commercial comparative fishing was conducted in three different licence areas, alternating between a traditional and the modified trawl. Five hauls were taken every 24 h, ensuring the same diurnal variation on both trawls. In all, 24 hauls (100 h) with the traditional trawl and 21 hauls (95 h) with the modified trawl were taken.

Results and discussion

Underwater video showed an apparently good agreement between model and full-scale trawls.

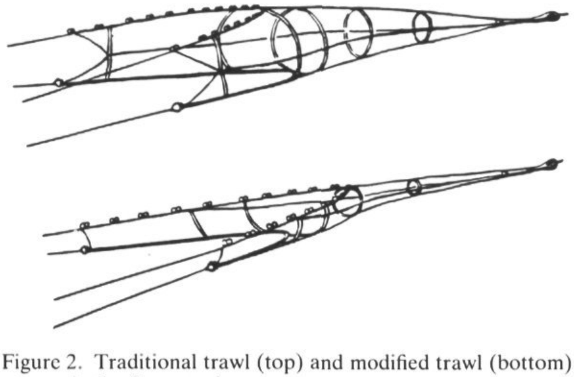

Figure 2. Traditional trawl (top) and modified trawl (bottom) as seen in the flume tank.

Most cod were seen entering the trawl close to the lower panel, just free of the sand clouds, leaving no hope of separating them from flatfish at this place. Only one cod was seen to escape above the approaching headline. Very few haddock were present on the grounds where the camera was used, and the effect of the new headline could not be detected. Further back in the trawl, the difference in cod and flatfish behaviour became more distinct. Most cod were seen rising to the upper panel, while most flatfish were gliding back near the lower panel. Cod were seen reaching the upper panel from the beginning of the middle section of the batings (panel width 110 meshes, Figure 1) and all the way down this section. At the back end of this section (panel width 61 meshes) the diameter of the trawl was about 1 m; flatfish were frequently seen close to the upper panel, and could presumably escape from the trawl if there were large meshes at this part of the trawl. Therefore, the 135 mm meshes were replaced by 540 mm meshes (i.e. each large mesh replaces 16 small meshes) in an area beginning where the panel width was 66 meshes and extending 38 meshes forward by 28 meshes in width. With these large meshes in the upper panel, many cod (64 out of 286 observed) were seen escaping from the trawl. Out of 124 flatfish, only 4 were seen escaping from the trawl. The vertical distribution of cod and flatfish, counted on underwater video, at different places in the trawl is shown in Figure 3.

The reason why cod rise inside the trawl is not known. Behind the ground gear the cod were seen keeping clear of sand clouds, so perhaps cod are avoiding annoying sand clouds not dense enough to be seen on the video. Also, the water flow inside the trawl may cause the rising action of cod. Fish react mostly by vision in front of the trawl (Glass and Wardle, 1989). This might also be true inside the trawl. If so, a coloured guiding system could strengthen the reaction, giving better escape of cod.

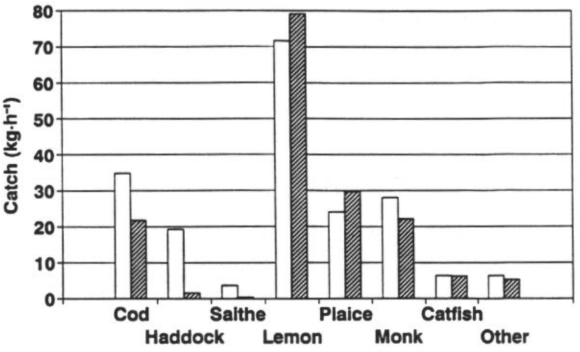

Figure 4. Catches (kg h^{-1}) in the traditional trawl (open columns) and in the modified trawl (shaded columns).

Comparative fishing confirmed the results seen on video camera. Catches in the two trawls are shown in Figure 4. Despite a large variation in catch and species composition between hauls in the two trawls (coefficient of variation between 0.3 and 1.5), there was a significant reduction of cod, haddock, and saithe in the modified trawl (one-tailed *t*-test, $p < 0.025$). For all other species there was no significant reduction. On average the catch of cod was reduced by 38% and catches of haddock and saithe were reduced by more than 90% in the modified trawl.

Although the effect of removing the front part of the upper panel could not be confirmed, it is believed to be the reason for the absence of haddock in the modified

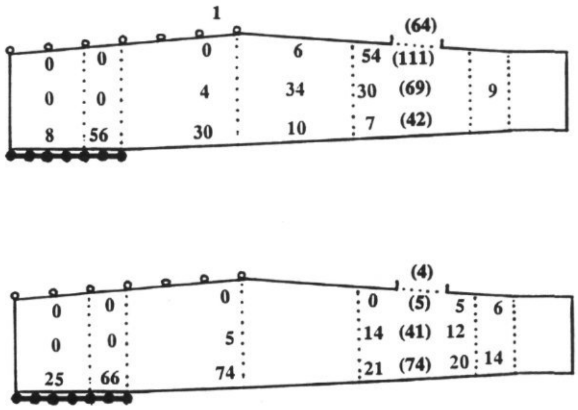

Figure 3. Vertical distribution of cod (top) and of flatfish (bottom) counted on underwater video at different places in the trawl. Numbers in parentheses were obtained after introduction of large meshes in the upper panel. Many fish on the lower panel, presumably most flatfish, were not recognized and therefore not counted.

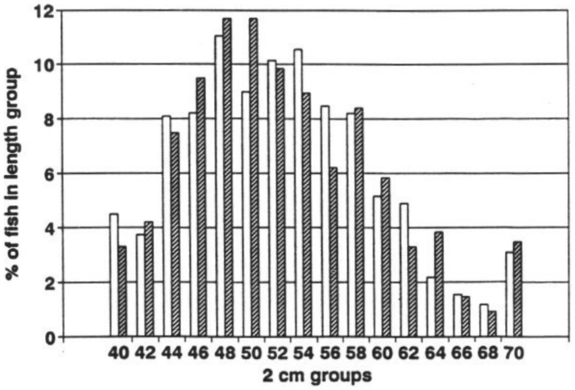

Figure 5. Length distribution of cod in the traditional trawl (open columns, n = 778) and in the modified trawl (shaded columns, n = 548). The 40 cm group represents all fish smaller than 42 cm, and the 70 cm group represents all fish larger than 70 cm in length.

trawl. On the other hand, it was seen from the video that the large meshes in the upper panel in the middle of the trawl body accounted for the reduction of cod in the modified trawl.

No difference was found in the length distribution of cod in the two trawls (Fig. 5). Day and night differences cannot be detected as the night was short at this time of year.

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Research on improving the species selectivity of bottom trawls in The Netherlands

B. van Marlen

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This paper describes current research on selectivity of bottom trawls conducted by the Netherlands Institute for Fisheries Research (RIVO-DLO) with emphasis on fish behaviour. The research is aimed at reducing unwanted by-catch in bottom trawling and beam trawling by changing the design of the net or the rigging. Some release of cod can result from raising the fishing line of a bottom trawl whilst leaving the groundrope on the seabed. Separation of whiting from cod was not complete. Large-meshed top panels in beam trawls are shown to release juvenile cod, but also a substantial amount of marketable whiting. Flatfish catches were hardly affected, but more research is necessary for definite conclusions. It is clear that relatively simple modifications in the design of fishing gears can improve species selectivity.

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Introduction

Fish stocks should be protected from overfishing and a sustainable level of exploitation should be guaranteed for future generations. It is commonly recognized that unwanted by-catch should be left in the sea. Juvenile fish may contribute to fisheries at a later age with augmented value. Non-target species may be caught at a later time or left to play their role in the ecosystem.

These objectives call for size- and species-selective fishing gears. The Netherlands Institute for Fisheries Research (RIVO-DLO) has given priority to gear selectivity studies following the recent international trend, and is carrying out several research projects on this important topic.

Main and Sangster (1982) observed that cod (*Gadus morhua*) dived in a trawl, while haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*) rose to the upper panel or over the headline. In an experimental split-level trawl fitted with a horizontal separator panel and two codends, most cod were found in the lower codend, and whiting and haddock in the upper one.

Project 1991/2 (Project in Biological Studies in the Fisheries Sector (1991/1992), funded by the EC) was aimed at creating a more directed fishery on whiting with bottom pair trawls, and releasing juvenile cod, by creating escape openings between the groundrope and the fishing line. The results are presented below.

Square-mesh selectivity experiments on flatfish conducted in Canada (Walsh *et al.*, 1989) confirm the finding in Europe that size selectivity for flatfish is not altered when using square-mesh netting (Fonteyne and M'Rabet, 1992). However, improved size selection was found for haddock and whiting in otter trawls with square meshes (Robertson and Stewart, 1988). FAR project TE-2-554 (Project in Fisheries and Agriculture Research Programme of the EC, contractors NL, B, and UK) aims at reducing the by-catch of roundfish in beam trawling whilst maintaining flatfish catches at existing levels by simple alterations to net design, creating larger escape openings in the top half of the net, and is described below. Studies on scale models and underwater observation play an essential role in the design of modified gears.

Project 1991/2 "Separation of cod and whiting in bottom pair trawling"

Materials

The research was carried out on RV "Isis" in cooperation with two chartered boats, KW-173 and KW-137 (phase 1), and on RV "Isis" alone (phase 2), in the spring of 1991. Gear design modifications in phase 1 were aimed at increasing the distance between the fishing line and the bobbin footrope, and reducing the number of vertical connecting chains. The standard gear (Conv748) is the Danish pair trawl No. 748B (mesh size 120 mm in fore part) with connecting chains of 0.15 m; the experimental gear (Exp748) is the same with connecting chains of 1.0 m (Fig. 1). In phase 2 a horizontal separator panel was inserted into trawl No. 748A (same as 748B with mesh size 200 mm in fore part) and a double codend was attached in order to investigate differences in behaviour by catch comparison. Towing speeds varied between 3.5 and 4.5 knots.

Methods

Catches were compared using the alternate haul technique in phase 1. The two commercial trawlers handled the various fishing gears, while RV "Isis" operated the Remotely Operated Vehicle (ROV) for direct observation. The position of the net was marked with floats connected to the warps ahead of the gear. All fish (landings) and all discards were sampled and measured in phase 1. In phase 2 all fish caught in the upper and lower codend were measured. Nine hours of video film were shot in phase 1 during 18 dives. Whiting was observed to seek escape routes in the upper parts of the net.

Data analysis

Four hauls in phase 1 with Exp748 could be compared with three with Conv748 in rectangle 37F3, and one haul for both gears in rectangle 34F4. The numbers of landings and discards were converted to 100 h of fishing.

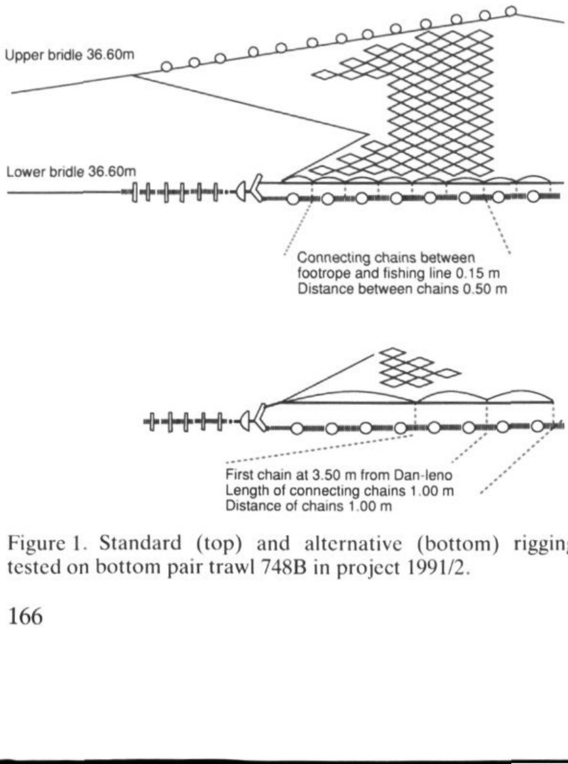


Figure 1. Standard (top) and alternative (bottom) rigging tested on bottom pair trawl 748B in project 1991/2.

Corresponding figures are given in Table 1. For phase 2, numbers of cod and whiting caught in all hauls were converted to 100 fishing hours for each area for both the upper and lower codends (Table 2).

Discussion of results

The experimental gear provided larger escape openings. It was felt that the rigging could still be optimized further. The video recordings showed that whiting did not react differently to both riggings of the Danish pair trawl.

A better escapement of small cod could occasionally be achieved with the experimental rigging, as could a higher catch of whiting. However, the results for both areas 37F3 and 34F4 were quite different for these species, suggesting that the number of hauls is too small for a statistically significant proof. The conclusions should therefore be regarded as preliminary. A higher percentage of cod was found in the lower codend for all areas fished (Table 2). This finding is consistent with observations made in behavioural studies. Contrary to expectation, higher percentages of whiting were also found in the lower codend, except for one area. A relatively low height (0.5 m) with the centre of the panel behind the bosom seemed to give the best separation of whiting, but a complete separation of cod and whiting could not be obtained.

Project TE-2-554 "Improved selectivity of fishing gears in the North Sea fishery – beam trawling"

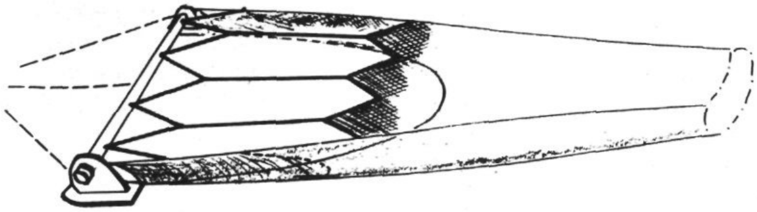
Materials

A typical 12 m tickler chain V-net was chosen as representative for the Dutch beam trawl fleet. Mesh sizes ranged from 260 mm in the top panel and 110 mm in the lower panel to 80 mm in the codend. Three configurations were selected for observation and trials at sea after model studies, namely a hexagonal mesh top panel and two versions of a large diamond-mesh top panel (Fig. 2).

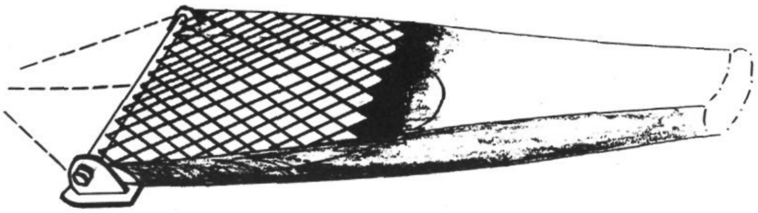
Methods

A total of 40 test runs (model tests were also done on a 9 m and a 10 m round net, produced by SEAFISH (UK) and RVZ (B)) were carried out in the SEAFISH flume tank in October and November 1991 on models at scale 1/5. The design of the large diamond-mesh top panel was improved. The selection of configurations to be tested at sea was based on estimated effect, technical feasibility, estimated costs, enforceability, and acceptability to the fishing industry.

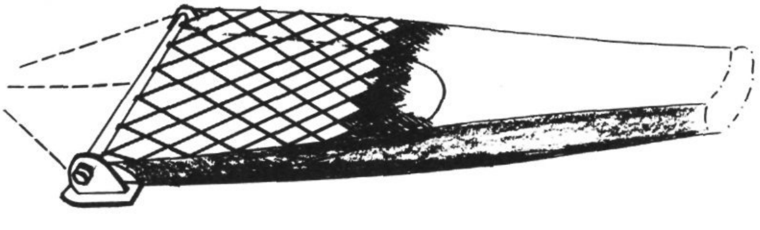
A first series of direct observations was done on RV "Tridens" in March 1992. The large mesh and hexagonal



Hexagonal mesh top panel



Large diamond mesh top panel
mesh size 2 m



Very large diamond mesh top panel
mesh size varying from 4.8 to 2 m

Figure 2. Three-dimensional impression of new designs of a 12 m beam trawl tested in project TE-2-554.

mesh top panels were observed with remotely controlled television and modified slightly.

Selectivity trials were conducted on RV "Tridens" in April 1992 with the 12 m, V-type beam trawls on fishing grounds in the North Sea. The experimental trawls were tested on parallel tows against a standard trawl. Before the tests it was established that both nets fished equally. Fishing was done between 16.00 and 10.30 the next morning to increase the chance of catching cod and whiting. The tow duration was approximately 2.5 h at speeds of 6–7 knots. Samples were taken if catches were large. The length of each fish in a sample was measured

Table 1. Cumulative number of fish caught converted to 100 hours of fishing for conventional and experimental riggings of gear 748B in project 1991/2 (phase 1).

Gear:	Conv748				Exp748			
Area	No. of fish	%	L (cm)	s.d.	No. of fish	%	L (cm)	s.d.
WHITING								
34F4	13 424	100	26.95	4.06	50 330	375	28.45	3.70
37F3	573 138	100	26.17	3.27	557 608	97	26.54	3.27
COD								
34F4	2 041	100	60.78	16.64	1 886	92	58.98	17.53
37F3	13 411	100	30.61	12.64	8 931	67	37.00	12.36

Table 2. Cumulative number of fish caught per area converted to 100 h of fishing in project 1991/2 (phase 2).

	Cod				Whiting			
Area	Upper codend	%	Lower codend	%	Upper codend	%	Lower codend	%
34F4	426	24.4	1 319	75.6	10 016	44.8	12 346	55.2
35F4	0	0	572	100	5 514	22.6	18 897	77.4
36F5	0	0	673	100	48 487	38.7	76 886	61.3
37F3	158	6	2 456	94	18 250	36.3	31 984	63.7
36F6	108	16.4	550	83.6	30.508	83.4	6 075	16.6
37F7	811	36.8	1 395	63.2	103 807	37.1	176 200	62.9
Total	1 503	17.7	6 965	82.3	216 582	40.2	322 388	59.8

Table 3. Results from comparative fishing experiments with a conventional and three experimental 12 m beam trawls on RV "Tridens" in April 1992, project TE-2-554.

Gear	Conventional beam trawl (S) Hauls 1–21				Hexagonal mesh top panel (P) Hauls 1–21			
	No. of fish	%	L (cm)	s.d.	No. of fish	%	L (cm)	s.d.
Plaice	15 043	100	25.48	3.95	13 898	92.4	25.41	4.03
Sole	4 288	100	29.06	3.83	4 492	104.8	28.78	3.75
Whiting	652	100	26.14	3.70	558	85.6	25.47	3.77
Cod	20	100	57.00	22.88	8	40.0	49.75	30.48
Gear	Conventional beam trawl (S) Hauls 22–43				Large (2 m) mesh top panel (P) Hauls 22–43			
	No. of fish	%	L (cm)	s.d.	No. of fish	%	L (cm)	s.d.
Plaice	6 708	100	26.69	4.09	4 859	72.4	27.15	4.41
Sole	2 317	100	29.80	3.74	2 052	88.6	29.75	3.87
Whiting	1 385	100	27.19	3.91	698	50.4	26.58	3.82
Cod	16	100	48.31	29.88	14	87.5	57.71	23.46
Gear	Conventional beam trawl (S) Hauls 44–57				Very large mesh (2–4.8 m) top panel (P) Hauls 44–57			
	No. of fish	%	L (cm)	s.d.	No. of fish	%	L (cm)	s.d.
Plaice	3 281	100	24.84	3.60	3 562	108.6	25.59	3.47
Sole	2 493	100	29.28	3.70	2 157	86.5	29.64	3.61
Whiting	800	100	27.39	3.15	356	44.5	28.04	3.52
Cod	324	100	27.78	3.43	156	48.1	28.13	4.08

and recorded by hand. Total numbers of fish and mean lengths are given in Table 3 for all three experimental gears for plaice (*Pleuronectes platessa*), sole (*Solea solea*), cod, and whiting.

The results indicate that fewer cod and whiting are caught in the trawls with large diamond meshes or hexagonal meshes in the top panel. During some night-time hauls, substantially fewer juvenile cod were caught in the net with the very large diamond-mesh top panel than in the standard net. The data indicate a possible loss of some flatfish for the experimental nets (Table 3), but the impression from weight comparison was that plaice and sole catches were hardly affected by the larger openings in the top panel.

Conclusions and recommendations

Although only a small number of hauls in the bottom pair trawl experiments were suitable for analysis, it is felt that by creating a larger opening between the footrope and the fishing line, catches of juvenile cod may be reduced. However, in some cases also a marked reduction in the catch of whiting was found. Inserting a separator panel with a trouser codend will not give complete separation of cod and whiting. Most cod appeared in the lower codend, and whiting were more equally distributed.

Juvenile cod may be offered more escape opportunities by inserting large diamond-mesh or hexagonal-mesh top panels in a beam trawl. The penalty might be a certain loss in marketable whiting, as fewer whiting were caught in the experimental gears, most above the minimum landing size, as this has been reduced to 23 cm from 1 June 1992.

The data indicate a possible reduction in numbers of flatfish with the large diamond-mesh top panels. The results, however, were not at all consistent over the full range of hauls. More experiments are therefore recommended.

The experimental large-mesh top panels did not provide any difficulties in gear handling. A noticeable decrease in gear drag, which might have been expected, was not found. Savings in net material can be expected, but little is known about endurance and maintenance of the new gears.

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The author feels very much indebted to the European Commission (DG-XIV), which supported the two projects described in this paper (1991/2 and TE-2-554), and to his colleagues both in the Netherlands (RIVO-DLO, IJmuiden) and in Belgium (Rijksstation voor Zeevisserij (RVZ), Ostend), as well as in the United Kingdom (Seafish Technology (SEAFISH), Hull).

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Selectivity in the codend and in the main body of the trawl

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The Japan–Russia Joint Survey has been conducted off the Kuril Islands and the Kamchatka Peninsula since autumn 1989. In this survey, two types of selectivity experiment were carried out. One was the cover net method to determine the size selection of walleye pollock (*Theragra chalcogramma*) using codends of 110 and 135 mm knotless square mesh, 110 mm knotless diamond and 110 mm knotted diamond with dual sheet structure (the conventional type). The other was the pocket net method to determine from which part fish could easily escape, by comparing the catch of 14 pocket nets attached at different parts of the main body. The conventional codend retained all sizes of fish. The square-mesh codend had a tendency to free small fish, compared with the diamond-mesh codend. Catches in the pocket nets increased toward the rear part of the main body, which suggests the likelihood of size selection in the main part of the net before the codend in addition to codend selection.

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Introduction

Recently, Japanese northern trawlers have mainly been operating in the fishing grounds off the Kuril Islands and the Kamchatka Peninsula. Their main targets are walleye pollock (*Theragra chalcogramma*), Pacific cod (*Gadus macrocephalus*), Atka fish (*Pleurogrammus monopteryginus*), Pacific ocean perch (*Sebastes alutus*), rock sole (*Lepidopsetta bilineata*), and so on. These demersal fishes are caught all together owing to their variable length and wide geographical distribution (Yamamoto *et al.*, 1992). For protecting the juveniles, the development of appropriate trawl gear is expected.

Experiments in relation to the selectivity of trawl codends have been actively conducted in European countries (Robertson, 1988). This type of trial is, however, new in the north-east Pacific Ocean. This paper describes a selectivity experiment conducted to back up the series performed in the Japan–Russia Joint Survey since 1989.

Materials and methods

Experimental operations were carried out from October 1989 to August 1991 on the fishing grounds off the coast of the Kamchatka Peninsula and off the Kuril Islands (Fig. 1), using a bottom trawl net towed by the Japanese northern trawler "No. 107 Seitoku-Maru" (349 gt, 2800 hp). The fishing grounds were between 86 and 270 m deep. The experimental gear used was typical commercial bottom trawl gear except for the codend.

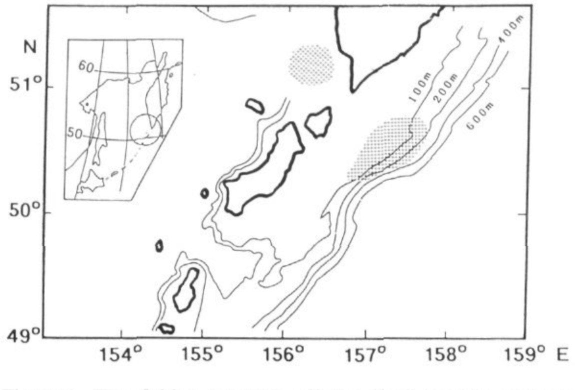

Figure 1. The fishing grounds off the Kuril Islands and the Kamchatka Peninsula. Stippled areas roughly designate where the experimental operations were carried out.

The experiment consisted of two parts. The first part was the estimation of size selection for walleye pollock using different types of codend with the cover net method. The mesh size and structure of each codend were 110 mm knotted diamond with dual sheet structure (the conventional type), 110 mm knotted diamond, knotless 110 mm diamond, 110 mm knotless square, and 135 mm knotless square. The length of 1 bar was 45 mm in 110 mm mesh, whether knotted or knotless, and 55 mm in 135 mm mesh. The 110 mm square mesh was compared with knotless diamond mesh of the same size using a trouser type codend. After each haul, all walleye pollock caught in the codend and the cover net were measured separately as fork length at 1 cm intervals. When the catch was big, 100 to 500 individuals were measured as a random subsample. The towing time was limited to 15–60 min after the trawl gear reached the bottom so as to avoid any masking effect. The towing speed was 3.5 to 4.5 knots.

The second part was to test the supposition that selectivity takes place in the main part of the net in addition to the codend. Fourteen diamond-shaped cuts, 1.5 m on a side, were made in the main body and pocket nets were attached. The catches of each pocket net were weighed separately and fork lengths of individuals caught were measured after the haul. Behaviour of the net during the operation was measured using a net-monitor (Koden; 50 kHz) and Scanmar. A timer-controlled underwater video camera (Inoue *et al.*, 1991) was also attached to observe the shape of the pocket nets and fish behaviour in the main part of the net.

Plans of the net and the codend used in these experiments are shown in Figures 2a–c and 3a–b.

Results and discussion

Figure 4 shows the size composition of walleye pollock caught in each experiment. The results of every study of fish size composition vary depending on the fishing season, location, and depth. Therefore, it is difficult to make strict comparisons between codends except when using the trouser codend. Each result has to be considered independently.

Selection curves for walleye pollock were fitted to logistic curves as shown in Figure 5 (Simpson, 1989). The three-point moving average method was used for determining the selection curve. Cases where the sum of a length class was fewer than 20 invididuals were omitted; such data were observed at the ends of the size composition. The data equal to 100% retention were set to 99% to accommodate the linearized form of the logistic curve. The 110 mm knotted diamond mesh with dual sheet structure retained all fish length classes (19–68 cm) and did not permit the determination of a selection curve. It seemed that the construction where the meshes lay one upon another obstructed the mesh openings and the escape of fish. In the case of the trouser codend study, the 110 mm knotless square-mesh codend released bigger individuals than did the 110 mm knotless diamond mesh. As shown in Figure 5, two selection curves were estimated for the same mesh size (110 mm diamond). This seemed to be explained by a difference in size composition. And in the case of the trouser codend, the side panels of codends facing each other cannot be expected to effect selection because of the close spacing. Therefore, only the top and outside panels are able to select the fish. The trouser codend is effective for comparing the size selectivity of different meshes under the same conditions, but there is a possibility that the result is different from the selectivity of a normal codend.

According to the results, the selection curve will change depending upon the size composition of the target species. Since selectivity of sizes and species occurs not only at the codend, it seemed reasonable also to investigate how efficiently fish are concentrated from the mouth of the main part of the net to the extension and to assess mesh selectivity in this part.

In the pocket net experiment, the main species in each catch were walleye pollock and Atka fish. Judging by the underwater video recordings, the pocket nets seemed to exert very small hydromechanical influences on the shape of the net. It was considered that the drag of the main part of the net and the trawl door was much greater (about 20 tons) than that of the pocket nets.

The catch in the pocket nets typically had a distribution pattern where the catch per pocket increased at the rear part of the main net (Table 1). Also the side-panel pocket nets caught considerably more fish than the top-panel pockets. The inclination of the side panel relative to the towing direction was different from that of the top panel. The fish were concentrated vertically from the net mouth, about 4 m in height, toward the extension, which is only about 2 m in height, along the top panel as shown in Figure 6. The fish were concentrated horizontally between the net mouth, about 30 m in width, and the extension, about 2 m in width, along the side panel. The difference in pocket catch thus depended mainly upon the structure of the main net.

The catch size compositions both in the codend and the pocket nets are shown in Figure 7. There was no difference between them. Notice that the Atka fish are smaller than the walleye pollock (Fig. 7). However, there was a linear relationship between the catch in the codend and the total catch in the pocket nets for each species (Fig. 8). The catch of Atka fish was smaller than that of walleye pollock in the pocket nets. This difference by species seemed to be caused by a difference in swimming ability, not visual reaction. The twine colour of the main body and the pocket nets was identical (dark green), therefore the contrast between the main part of the net and the pocket nets is considered to be very slight in such dark fishing grounds (Jerlov, 1976). Even if the fish can see the net, the distance to it would be very short. This motion was confirmed by observations with the underwater video camera. It was observed that the smaller Atka fish swished their tails rather more actively than the larger walleye pollock.

The results mentioned above suggest the likelihood of size selection of the main body at the rear part of the side panel near the extension. However, this selection varies with species.

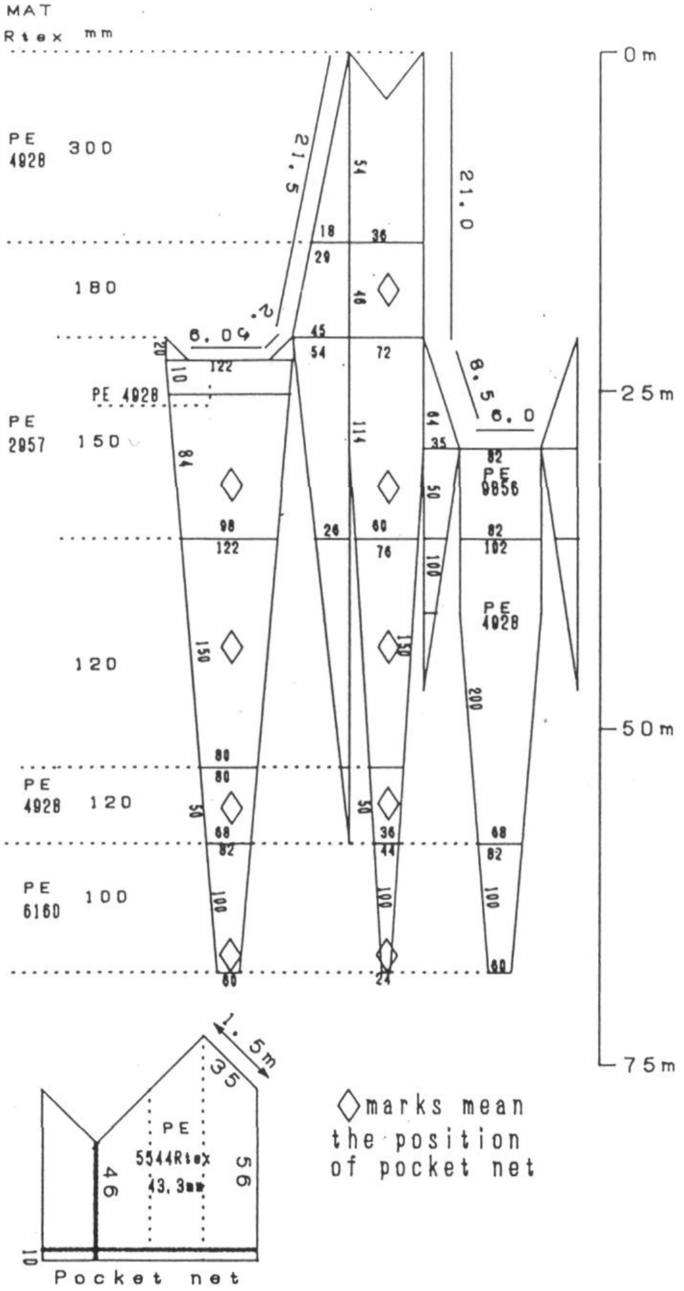

Figure 2a. Plan of the main net used by "No. 107 Seitoku-Maru".

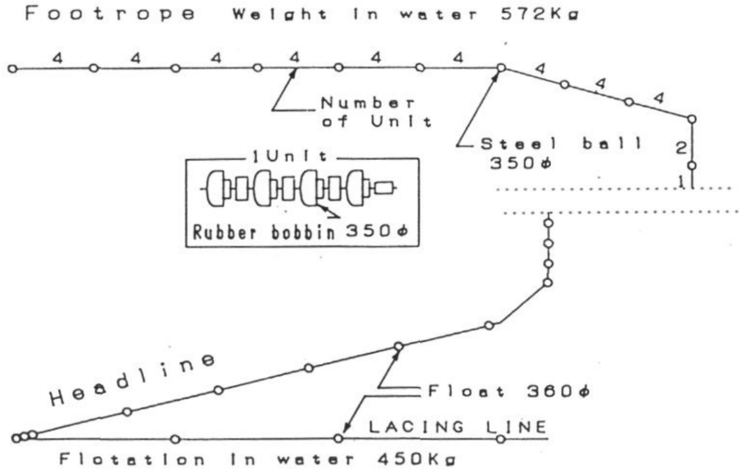

Figure 2b. Arrangement of the footrope and the flotation.

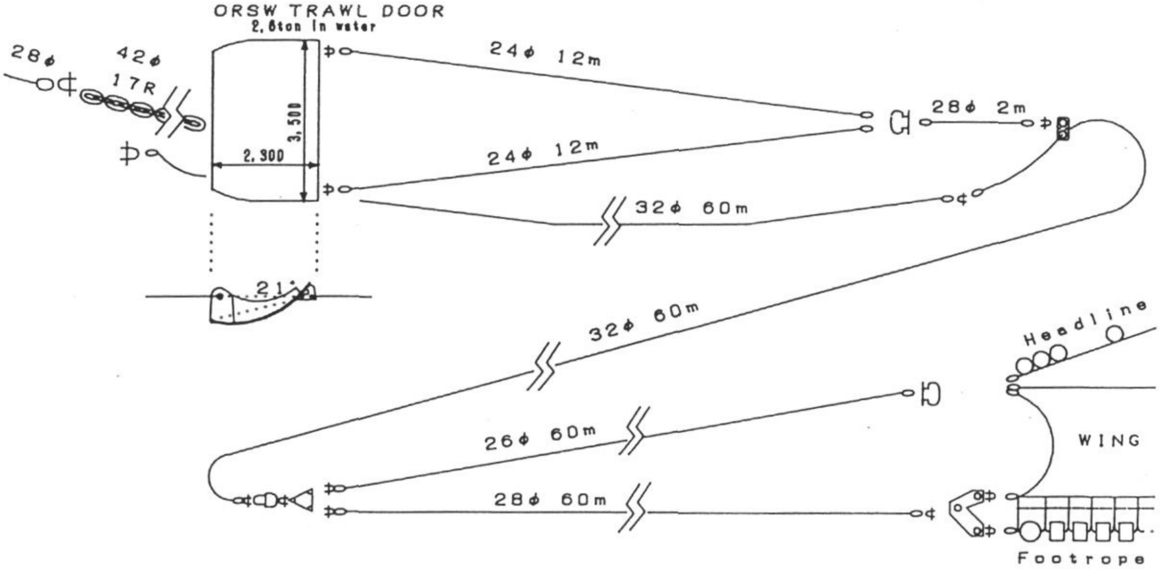

Figure 2c. Arrangement of the bridles and the trawl door.

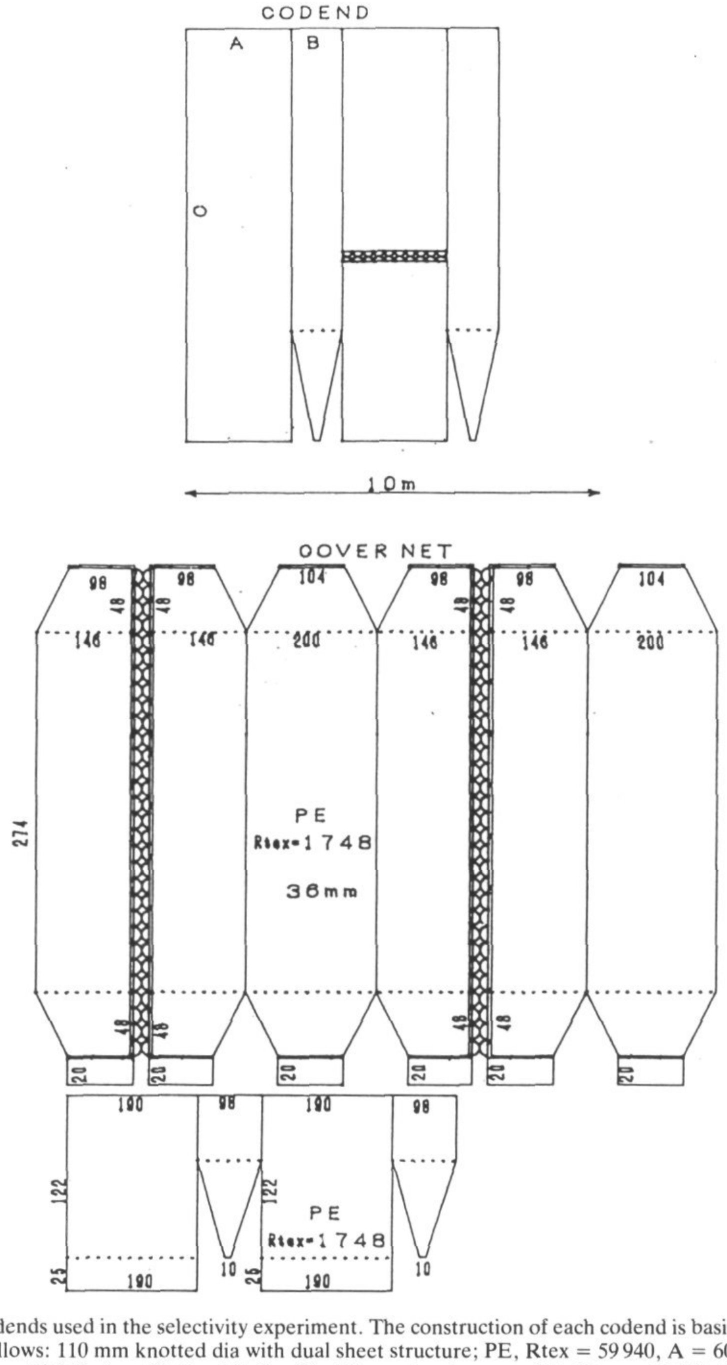

Figure 3a. Plan of codends used in the selectivity experiment. The construction of each codend is basically similar. The details of each codend are as follows: 110 mm knotted dia with dual sheet structure; PE, Rtex = 59 940, A = 60, B = 25, C = 94. 110 mm knotted dia; PE, Rtex = 59 940, A = 60, B = 25, C = 94. 135 mm knotless squ; PE, Rtex = 46 620, A = 38, B = 18, C = 150.

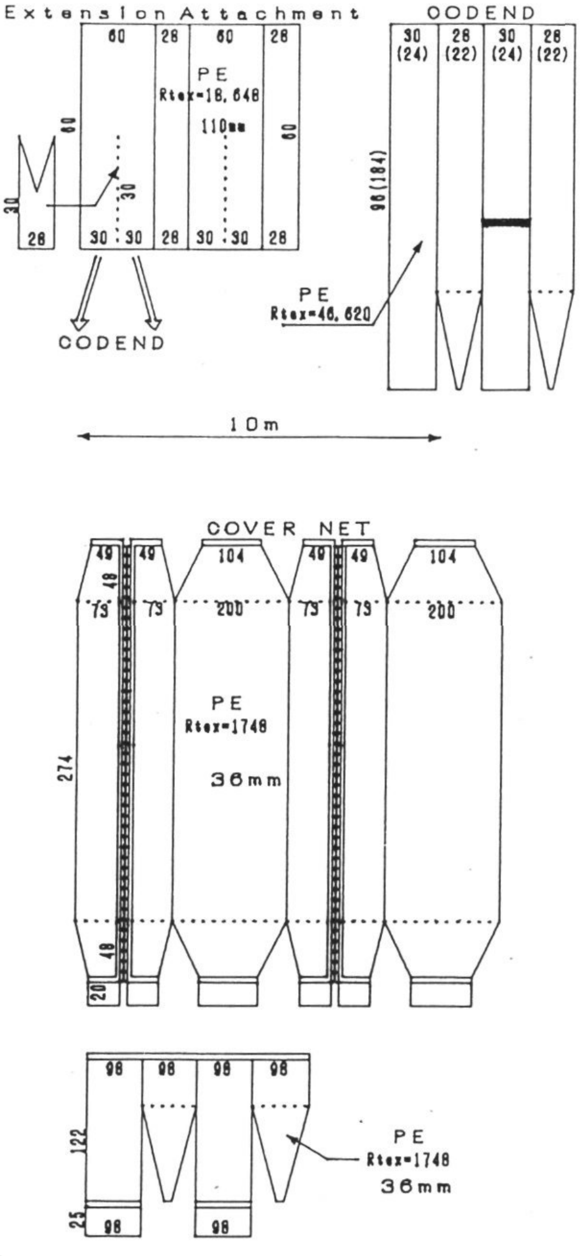

Figure 3b. Plan of the trouser codend. Numbers in parentheses are the number of bars of square mesh.

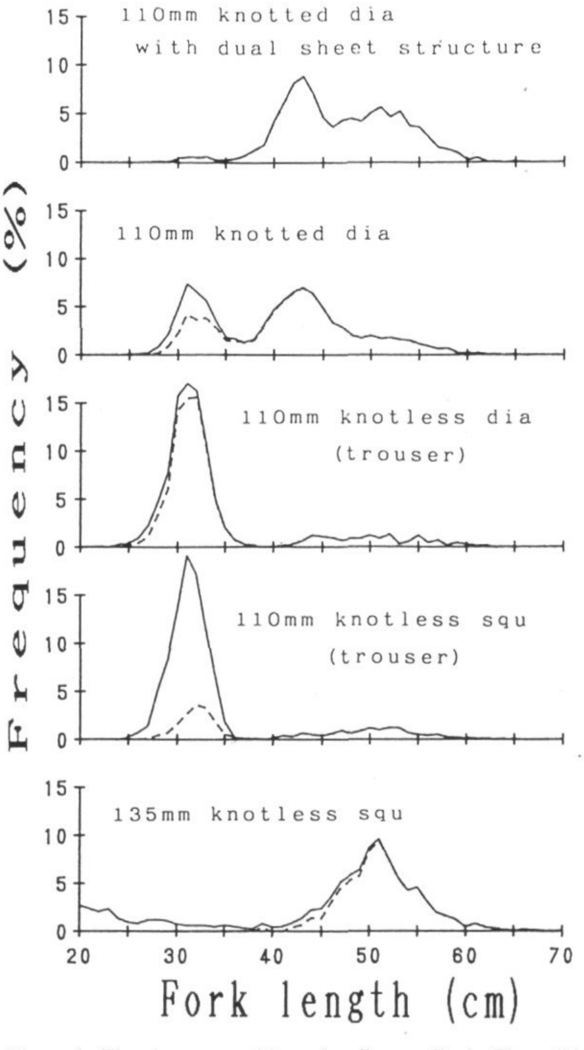

Figure 4. The size composition of walleye pollock. The solid line shows the total catch (codend + cover net). The dotted line shows the catch in the codend.

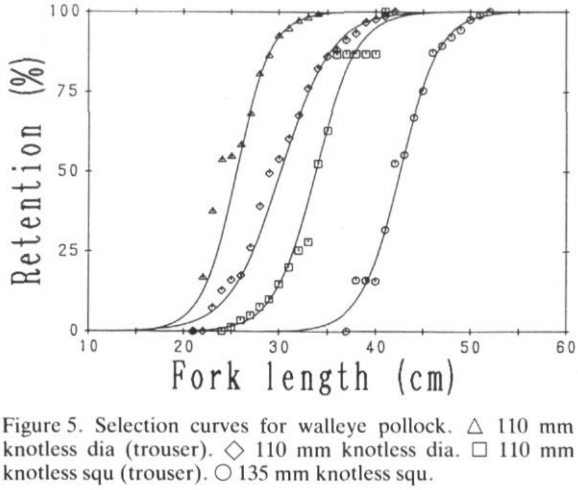

Figure 5. Selection curves for walleye pollock. △ 110 mm knotless dia (trouser). ◇ 110 mm knotless dia. □ 110 mm knotless squ (trouser). ○ 135 mm knotless squ.

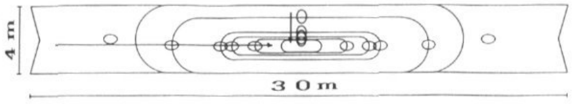

Figure 6. Front view of the trawl net, estimated from the wing distance and the head rope height. The oval marks show the positions of pocket nets. The arrows show the direction of movement of fish in the main net.

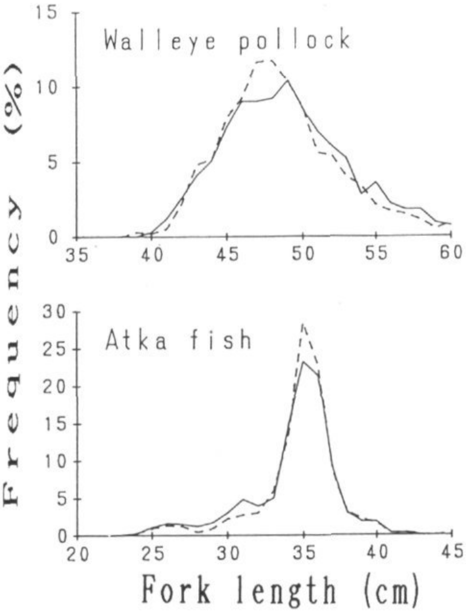

Figure 7. Size composition of walleye pollock and Atka fish caught in the codend and the pocket nets. Catches of pocket nets were measured all together. The solid line shows the catch in the pocket nets. The dotted line shows the catch in the codend.

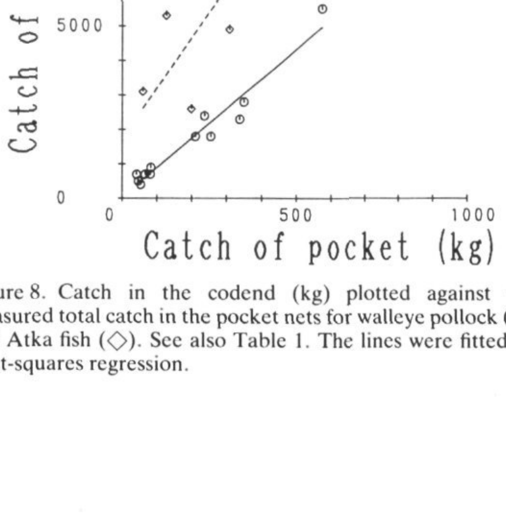

Figure 8. Catch in the codend (kg) plotted against the measured total catch in the pocket nets for walleye pollock (○) and Atka fish (◇). See also Table 1. The lines were fitted by least-squares regression.

Table 1. Summary of catches in the pocket nets and the codend.

Haul	Position	Front part →→→→→→→→		Rear part				Codend	
		of main body		(kg)		of main body			
no.	of pocket	1	2	3	4	5	Total	(ton)	Species
1	Top panel		0	0	33.0	18.6	339.6	2.23	Walleye pollock
	Side panel (L+R)	11.6	45.2	44.2	88.4	98.6			
2	Top panel		0.8	2.7	4.7	18.2	237.8	2.37	Walleye pollock
	Side panel (L+R)	12.9	33.4	34.9	62.6	67.6			
3	Top panel		0	5.2	45.9	25.2	575.2	4.69	Walleye pollock
	Side panel (L+R)	50.1	88.8	88.5	144.2	127.3			
4	Top panel		0	0	3.5	2.0	54.0	0.44	Walleye pollock
	Side panel (L+R)	3.0	11.0	14.0	8.0	12.5			
5	Top panel		0	0.8	0.8	1.5	42.8	0.67	Walleye pollock
	Side panel (L+R)	1.4	8.0	11.8	11.1	7.4			
6	Top panel		0	0	12.7	2.7	83.6	0.91	Walleye pollock
	Side panel (L+R)	0.9	16.4	27.3	11.8	11.8			
7	Top panel		0.7	1.7	8.4	16.9	211.5	1.77	Walleye pollock
	Side panel (L+R)	8.3	35.8	47.3	53.2	39.2			
8	Top panel		0	0.7	4.8	0	47.0	0.51	Walleye pollock
	Side panel (L+R)	3.1	8.2	6.0	13.4	10.8			
9	Top panel		0	3.2	16.4	2.4	255.3	1.80	Walleye pollock
	Side panel (L+R)	11.2	49.7	40.8	82.7	48.9			
10	Top panel		0	2.8	1.5	2.6	67.1	0.69	Walleye pollock
	Side panel (L+R)	3.3	22.0	17.0	10.9	7.0			
11	Top panel		0	0	6.0	2.3	82.0	0.68	Walleye pollock
	Side panel (L+R)	3.7	20.4	19.8	17.6	12.2			
12	Top panel		0	0	18.4	19.0	351.0	2.78	Walleye pollock
	Side panel (L+R)	9.3	113.0	95.1	63.8	32.4			
13	Top panel		0	0.4	5.0	0.9	127.2	5.35	Atka fish
	Side panel (L+R)	22.5	13.7	28.0	31.9	24.8			
14	Top panel		0	0	3.0	1.3	60.3	3.06	Atka fish
	Side panel (L+R)	17.5	9.7	15.0	8.1	5.7			
15	Top panel		0	19.0	48.4	23.0	409.3	8.64	Atka fish
	Side panel (L+R)	10.8	19.0	32.8	155.3	101.0			
16	Top panel		0	17.4	10.0	28.4	309.6	4.86	Atka fish
	Side panel (L+R)	67.4	93.9	33.1	27.4	32.0			
17	Top panel		0	1.3	5.2	12.4	199.1	2.63	Atka fish
	Side panel (L+R)	22.5	64.8	16.5	19.0	57.4			
18	Top panel		2.2	3.8	62.5	4.8	688.2	12.14	Atka fish
	Side panel (L+R)	77.9	25.0	49.5	162.5	300.0			
19	Top panel		0	11.0	25.0	50.0	769.7	12.94	Atka fish
	Side panel (L+R)	4.0	29.7	125.0	200.0	325.0			

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We are grateful to the Captain and the crew of "No. 107 Seitoku-Maru" for their help during the cruise.

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Size selectivity of rigid sorting grids in bottom trawls for Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*)

Roger B. Larsen and Björnar Isaksen

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During 1990 and 1991, selectivity experiments with rigid sorting grids in the aft sections of a trawl were carried out on board different trawlers along the coast of northern Norway. Selectivity data on cod (*Gadus morhua* L.) and haddock (*Melanogrammus aeglefinus* L.) are presented and discussed in relation to other methods and the observed behaviour of escapees. The stainless steel sorting grids had a bar distance of 55 mm and covered an area of 3.2 m^2, replacing a part of the upper panel in the extension piece ahead of the codend. To determine the size selectivity achieved with this system, the trawl codend was blinded by a 48 mm inner net, and fish escaping through the grids were collected into a 48 mm cover placed over the grids. Selection ranges on cod and haddock ranged from 4.6 cm to 8.5 cm, while 50% retention lengths of 47.8 cm to 50.2 cm were obtained. A camera on a towed vehicle observed fish behaviour inside the trawl and during escape. Additionally, a scanning sonar monitored gear geometry during the experiments.

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Introduction

There seems to be general agreement among gear scientists around the world that slight changes of mesh size in normal diamond-mesh codends may not serve the basic intentions of improved or altered selectivity (MacLennan, 1992). During studies of codend selectivity, many variables have been shown to influence the codend size selection of fish in trawls and other mobile gears (Pope *et al.*, 1975). One of the largest problems to overcome is the reduction in effective mesh opening as the codend catch increases (Engås *et al.*, 1989). The use of divers and underwater cameras in studies of fish behaviour inside gears is fundamental to understanding how to exploit this behaviour for selectivity purposes (Wardle, 1989).

The basic idea behind both square-mesh panels and rigid sorting grids is the need for stable openings in the codend through which effective escape can occur despite changing towing speeds, catch sizes, etc. Notwithstanding very promising results with square-mesh netting in codends (Cooper and Hickey, 1989; Robertson, 1989), this technique has been found unusable in the Barents Sea, owing mainly to problems with redfish (*Sebastes* spp.) masking meshes and reducing selectivity at larger catch volumes (Isaksen and Valdemarsen, 1989; Larsen, 1989a).

Observations of diamond-mesh codend escape show that fish often panic inside the codend; some of the escaping fish are squeezed through the mesh and some hit the mesh opening and wriggle out (Main and Sangster, 1988). Ordinarily codend escape will only occur through a small area of the codend, i.e. a few rows of mesh in front of the accumulating catch (Engås *et al.*, 1989). As an attempt to overcome some of the selectivity problems already mentioned, the development of sorting grids for bottom fish trawls was begun in late 1989 (Larsen, 1989b).

Materials and methods

The experiments presented in this paper were carried out on fishing grounds along the coast of Finnmark, northern Norway, from 27 August to 9 September 1990 (on board the 52 m "Anny Krämer") and 25 August to 8

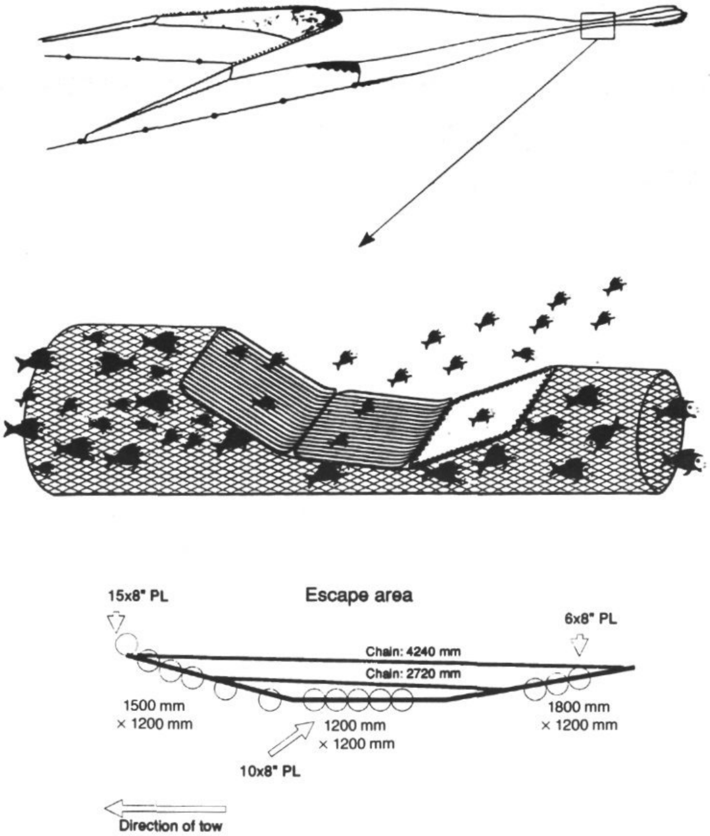

Figure 1. (Top) An indication of where the sorting grids are placed in the existing trawl, (middle) a sketch of the working principle of rigid sorting grids (Sort-X model), and (bottom) details of the construction. The grid area covers 3.2 m^2 and the system made of stainless steel is buoyed with 8″ (Ø200) plastic (PL) floats.

September 1991 (on board the 47 m "Skjervöyfisk"). In both periods normal bottom trawls were used, i.e. 424 meshes × 150 mm "Alfredo" designs equipped with 75 m bobbin ground gears. As a standard the "butterfly rig", i.e. short bridles (10.3 m) and long sweeps (140 m), 7–8 m^2 and 1800–1950 kg otter boards were used. Towing speed varied from 4.0 to 4.5 knots.

The sorting grids replaced a part of the upper panel in the extension piece, i.e. the tubular section between the belly and the codend (Fig. 1). The grids (Sort-X model) were made of stainless steel and consisted of three sections joined together. Two separate grids with fixed bar distance of 55 mm were connected to a polyvinylchloride-canvas-covered steel frame, the main function of which was to guide escaping fish away from the trawl and to keep the system balanced during operation. The system weighed about 90 kg, and neutral buoyancy was achieved with plastic floats. Once in the sea, the system opened and was kept in a steady position by using chains. The angle of attack is theoretically close to 25° in the first part of the system (Fig. 1).

To estimate the size selectivity obtained with grids, escaping fish were collected in a 23 m long cover made of 48 mm polyethylene (PE). In total 7 plastic floats (200 mm) were placed along and on top of the cover (Fig. 2). To avoid biased selectivity data, the normal 135 mm polyamide (PA) codend of the trawl was simultaneously blinded by a 48 mm PE inner net. Length was measured as total length to the nearest cm for samples of fish (cod and haddock) from both codend and cover. The length–frequency distributions, adjusted for the total numbers of fish, form the basis of further calculations of selection curves and parameters such as selection range and 50% retention length. Comparing the catch in the cover with that in the trawl codend, the sorting grid size selectivity (S_i) of fish in size group i was established as:

$$S_i\ (\%) = N_i ce/(N_i ce + N_i co),$$

where N_i is the number of fish in size group i from the codend (ce) and the cover (co). Selection curves (ogives) were plotted as 3-point moving averages showing the retention percentage by the sorting grids for any fish size. Selection ranges ($L_{75\%} - L_{25\%}$) and 50% retention lengths ($L_{50\%}$) were calculated.

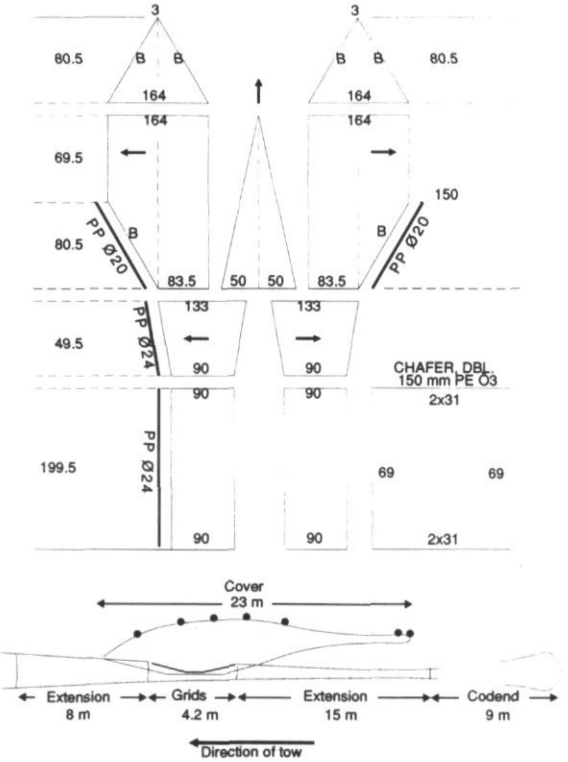

Figure 2. (Top) Construction of the 48 mm (full mesh size) polyethylene (PE) cover used to collect escaping fish during the experiments and (bottom) an illustration of the observed shape of it during operation. The lengths of the cover and different sections of the codend with extensions reflect the layout during the experimental periods.

Underwater observations

A towed and remotely operated vehicle (ROV) with a low-light underwater camera was used during the experimental periods to study both fish behaviour and the function of the sorting grid system during towing. The observations were made at depths of 50 to 90 m in natural daylight and lasted for about 30 min. Owing to a visibility of 10–15 m, it was possible to observe the behaviour of fish entering the area of the sorting grids and at closer distances, to examine how small fish escaped between the bars. In addition to these observations, a Simrad FS 3300 scanning sonar placed on the ROV was used to make geometrical measurements of the sorting system and the cover on top of it.

Results

As fish approached the sorting grid area they became more active, turned and started to swim along the towing direction just in front of or underneath the sorting grids. After a few seconds, fish started to seek towards the sorting grids and fish small enough to pass between the bars escaped rapidly by rising through the system without changing their normal swimming position (horizontal plane). Larger fish also attempted to escape.

Apart from a few hauls with broken covers owing to large quantities of escaping fish (exceeding an estimated 3–3.5 tonnes), the technique using the PE cover to collect escaped fish functioned as intended. ROV observations had to be made in shallow waters owing to technical problems and limitations with the vehicle at greater depths.

The size and construction of the cover ensured a good spacing between the sorting grids and the upper part of the cover. By scanning sonar examinations, this distance was measured to be almost 4 m during towings, thus leaving a large space of free water for the escaping fish. No panic movements of the escaping fish were seen as they passed between the bars of the grids and entered the cover. No major differences with respect to escape behaviour were seen between hauls with and without the cover over the grids.

The selectivity results when using the 55 mm sorting grids are presented as selectivity curves for cod and haddock (Figs. 3 and 4) obtained for single hauls during comparable conditions (depth, species, and size composition) in the two periods. The 50% retention lengths and the selection ranges achieved with the 55 mm grids are given in Table 1. Total numbers of fish and numbers within the selection range are listed.

Discussion

Isaksen *et al.* (1990) found that 50% retention lengths decreased and selection ranges increased for both cod and haddock as catch sizes grew. Despite the masking effect discovered during covered codend hauls, similar results were achieved during trouser trawl codend experiments. The most likely explanation for these results

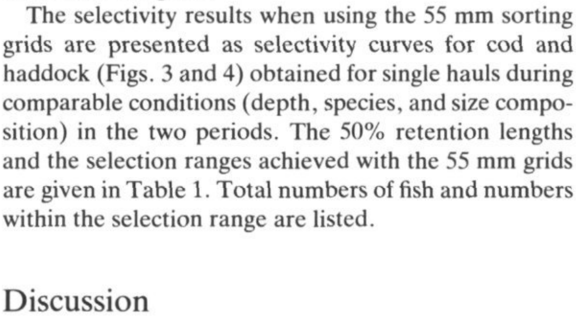

Figure 3. Selectivity curves obtained for cod (*Gadus morhua* L.) during experiments in the periods 27 August to 9 September 1990 (solid curve) and 25 August to 8 September 1991 (broken curve) with the 55 mm Sort-X on fishing grounds along the coast of northern Norway.

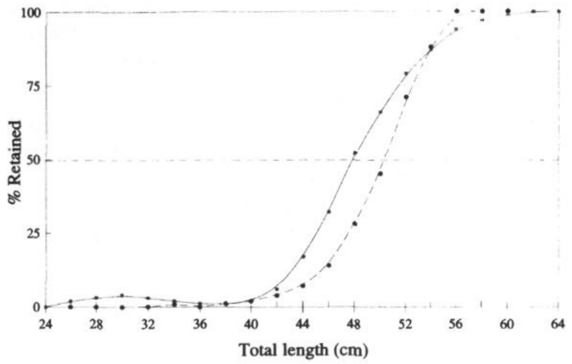

Figure 4. Selectivity curves obtained for haddock (*Melanogrammus aeglefinus* L.) during experiments in the periods 27 August to 9 September 1990 (solid curve) and 25 August to 8 September 1991 (broken curve) with the 55 mm Sort-X on fishing grounds along the coast of northern Norway.

is reduced effective mesh openings with increased catch and hence drag of the codend. The 50% retention lengths of cod and haddock obtained with 55 mm sorting grids are comparable to those achieved with small catches in 135 mm codends. During trouser trawl experiments (135 mm codend), selection ranges of 14.2 cm and 16.1 cm for cod and haddock, respectively, were obtained (Isaksen *et al.*, 1990) for catch sizes comparable with those in the grid experiments.

The effects on grid selectivity of using the cover and codend blinder were examined during May 1990 (Larsen, 1990). The size composition of fish in the blinded trawl codend did not differ between hauls with and without the cover. Furthermore, only a few cod within the size range of 55 to 75 cm, i.e. the upper part of the selection curve, escaped the codend when the blinder was removed. The size distributions of smaller cod (35 to 55 cm) and haddock (40 to 70 cm) did not differ between the blinded (48 mm) codend and the normal 135 mm codend.

Fish behaviour and escape may be the result of a very complicated set of stimuli. On the deeper fishing grounds and during darkness keywords to explain grid escape may be water flow, grid angles and the size of the escape area, whereas in shallower waters visual stimuli may be more important and vision may be the dominant sense. Owing to the technical limitations of underwater cameras, however, all observations on fish behaviour and escape have so far been made in shallow waters (working to a maximum depth of 150 m) and in conditions of relatively high levels of light. During the grid escape observations (at depths of 50–90 m during daytime), fish did react to the grid section, i.e. they turned just in front of the grids and held station by swimming for a few seconds before escaping rapidly between the bars. In a comparable manner fish have been observed to escape, or make attempts to escape, as soon as they enter an area of square mesh netting in trawls (Engås *et al.*, 1989). One likely explanation for this reaction may be a change of light penetrating the trawl where the net changes from normal diamond mesh to square mesh. Square mesh with a larger distance between opposite bars permits more light to penetrate the codend.

The given angle of attack of the first sorting grid reduces the distance between the grids and the lower panel of the net from about 80 cm to 20–30 cm. The aft section of the sorting system, i.e. the PVC-canvas covered frame, acts like a reversed kite during towing and hence ensures a narrow entrance into the codend behind it. The likelihood that fish will encounter the sorting system is therefore high owing to its geometrical shape, and the poor swimming ability and speed of smaller fish (Wardle, 1977) when related to normal trawl towing speeds.

Successful escape through a (codend) mesh is achieved when fish are able to hit the mesh opening precisely. However, to do so, fish must change their swimming position from a horizontal to an upright and vertical swimming position, which will be more difficult at higher water velocities. Finally, escape success will depend upon the strength of fish to wriggle their body through the flexible mesh. No principal differences between diamond-mesh and square-mesh codends are observed with respect to the escape pattern of fish (Engås *et al.*, 1989). The major difference between a codend mesh and the opening between the bars in the grids is the *length* of the escape area. Every slot in the

Table 1. Single haul results on 50% retention lengths and selection ranges obtained with the 55 mm Sort-X in bottom trawls during 27 August to 9 September 1990 ("Anny Krämer") and 25 August to 8 September 1991 ("Skjervöyfisk").

Species	Year	50% retention length (cm)	Selection range (s.r.) (cm)	Number of fish	Number within s.r.
Cod (*Gadus*	1990	49.6	8.5	1000	369
morhua L.)	1991	49.5	7.4	440	135
Haddock	1990	47.8	6.3	4920	1401
(*Melanogrammus*	1991	50.2	4.6	3026	213
aeglefinus L.)					

grids has a fixed opening of 55 × 750 mm. Fish are thus given more time to escape by a factor of 6–7 compared with a diamond 135 mm mesh. The size and shape of the escape area of the grids may explain why fish appear to escape more easily, and smoothly, than through codend meshes.

Acknowledgements

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Swimming speeds of marine fish in relation to fishing gears

Pingguo He

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Swimming ability plays a vital role in the survival of fish in terms of catching a prey and escaping from a predator or a fishing gear. Knowledge of how fish swim and how well they can swim is very important in the design and operation of selective and energy-conserving commercial fishing gears, and in fisheries resource assessment through better understanding of selectivity and efficiency of survey trawls. This paper summarizes recent findings of swimming performance in marine fishes and discusses how a change in swimming ability due to biological and environmental conditions and how a change in trawl operation can influence the size selectivity of a trawl. Special attention is paid to commercially important species, including mackerel (*Scomber scombrus*), herring (*Clupea harengus*), cod (*Gadus morhua*), and saithe (*Pollachius virens*).

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Introduction

Many contributions have been made since the 1920s on how, and how well, fish swim (see Beamish, 1978; Videler and Wardle, 1991). However, our understanding of the swimming ability of commercial marine fishes and their swimming behaviour near fishing gears is very limited. Yet knowledge of fish behaviour has become increasingly important in present-day fisheries. Commercial fishing operations have come to such a stage that operators are required only to catch certain species of particular sizes, using specified fishing gears at the specified location and time. Fisheries scientists conducting survey fishing operations use the same fishing gear in a vast area, hoping for a constant and known efficiency and selective performance of the gear over space and time.

Fish swimming speeds have been reviewed by Blaxter (1969), Beamish (1978), and more recently by Videler and Wardle (1991), and underwater observations of fish behaviour near towed trawls by Wardle (1983, 1986, 1989). This paper summarizes recent findings concerning the swimming capacity of commercial marine fishes, combined with those from field observations of fish swimming near fishing gears, to explore the selectivity of a trawl codend and how it is affected by the way fish swim and their swimming ability.

Species mentioned in the text are bluefin tuna (*Thunnus thynnus* L.), cod, or Atlantic cod (*Gadus morhua* L.), herring (*Clupea harengus* L.), jack mackerel (*Trachurus japonicus* (Temminck and Schlegel)), mackerel, or Atlantic mackerel (*Scomber scombrus* L.), Pacific mackerel (*Scomber japonicus* Houttuyn), and saithe (*Pollachius virens* (L.)).

Swimming speeds: mackerel as an example

The Atlantic mackerel is by far the most completely studied fish species in respect to swimming performance. Here mackerel is taken as an example to define the swimming speeds of fish. Recorded swimming speeds of mackerel range from a minimum of 0.4 L s^{-1} (body lengths per second, 0.32 m specimen) to a maximum of 18 L s^{-1} (0.31 m specimen). Figure 1 summarizes swimming speeds, endurance, body attack angle, and the use of swimming muscles at different speeds.

The Atlantic mackerel has no swimbladder and is heavier than seawater, therefore it has to swim constantly in order to generate lift to keep itself from sinking. The minimum swimming speed (U_{min}) of 0.4 L s^{-1} was recorded when the fish was swimming at a body attack angle of 27° (He and Wardle, 1986). Without body tilt, mackerel must swim at a minimum speed of 1 L s^{-1}. The preferred swimming speed (U_p) of mackerel was between 0.9 and 1.2 L s^{-1} when cruising around a 10 m diameter annular tank (He and Wardle, 1988). Mack-

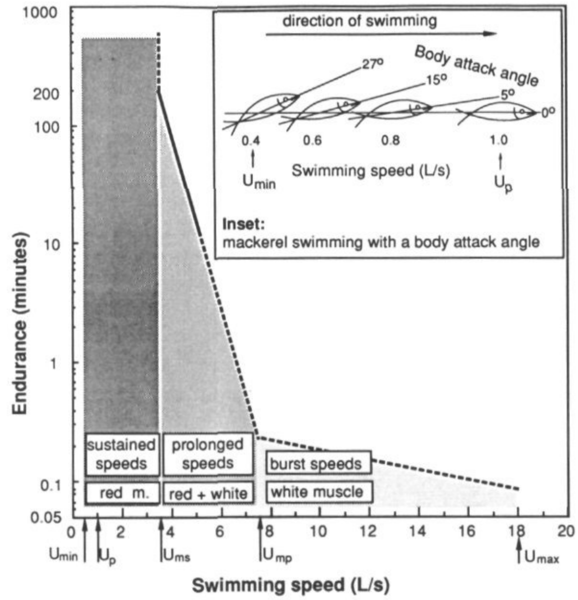

Figure 1. Swimming speeds (in body lengths per second) of the Atlantic mackerel (*Scomber scombrus* L.) from the lowest to the highest value recorded, plotted against endurance. Use of different types of muscles at different speed ranges is indicated. Inset: mackerel swimming with a body attack angle at speeds below U_p. See text for explanation.

erel swim at speeds below U_p only when space is restricted in a laboratory tank (He and Wardle, 1986) or when the light level is very low ($<10^{-6}$ lux) (Glass *et al.*, 1986). Many neutrally buoyant species can stop swimming; their minimum swimming speed is therefore equal to 0.

Mackerel can swim between 1 and 3.5 L s^{-1} indefinitely without leading to exhaustion (He and Wardle, 1988). This speed range is called the sustained swimming speeds, at which mackerel cruise voluntarily in large tanks and at sea, and during migration and feeding. When the swimming speed exceeds 3.5 L s^{-1}, limited endurance leads to exhaustion. This 3.5 L s^{-1} is called the maximum sustained swimming speed (U_{ms}). In practice, U_{ms} is the maximum swimming speed with an endurance equal to or greater than 200 min.

For swimming speeds greater than U_{ms}, the higher the speeds (U), the shorter the endurance (E). In mackerel, the relationship between E (in min) and U (in L s^{-1}) can be expressed in semi-log regression as (He and Wardle, 1988): $\mathrm{Log}E = -0.96U \times 5.45$. The maximum swimming speed involving power from the red muscle may be predicted in the same way as Wardle (1975) did with the white muscle. The fastest red muscle contraction time is about twice that of the white muscle in mackerel (He *et al.*, 1990). These authors predicted that at swimming speeds above 7.5 L s^{-1}, the red muscle will become ineffective as an energy source for swimming, owing to simultaneous contraction of muscle on both sides. This predicted 7.5 L s^{-1} swimming speed is called the maximum prolonged swimming speed (U_{mp}) and the range of speeds between U_{ms} and U_{mp} is called prolonged swimming speeds. The white muscle as well as the red muscle is used for swimming at the prolonged speeds.

Speeds beyond U_{mp} are called burst speeds, at which only the white muscle effectively contributes to the energy required for swimming. The white muscle operates anaerobically and its energy reserve can be depleted in a matter of seconds at burst speeds. The maximum swimming speed (U_{max}) of mackerel ever recorded is 18 L s^{-1}, which is very close to the predicted U_{max} from white muscle contraction time of 19 L s^{-1} at 12°C (Wardle and He, 1988).

The maximum sustained swimming speed

The maximum sustained swimming speed (U_{ms}) marks the upper limit of the sustained speeds (without leading to exhaustion) and the lower limit of the prolonged speeds (leading to exhaustion). It has been demonstrated by monitoring muscle activities in 0.15 m long jack mackerel that the red muscle only is used at swimming speeds up to U_{ms} of 6.2 L s^{-1}, while the white muscle joins in at speeds beyond U_{ms} (Xu, 1989).

The force generated from a muscle is related to the cross-sectional area of the muscle (Ikai and Fukunaga, 1968). It is thus not surprising that pelagic fish species possessing thick red muscle achieve a higher U_{ms}. For example, herring and saithe each of 0.25 m length have a maximum lateral red muscle cross-sectional area of 0.85

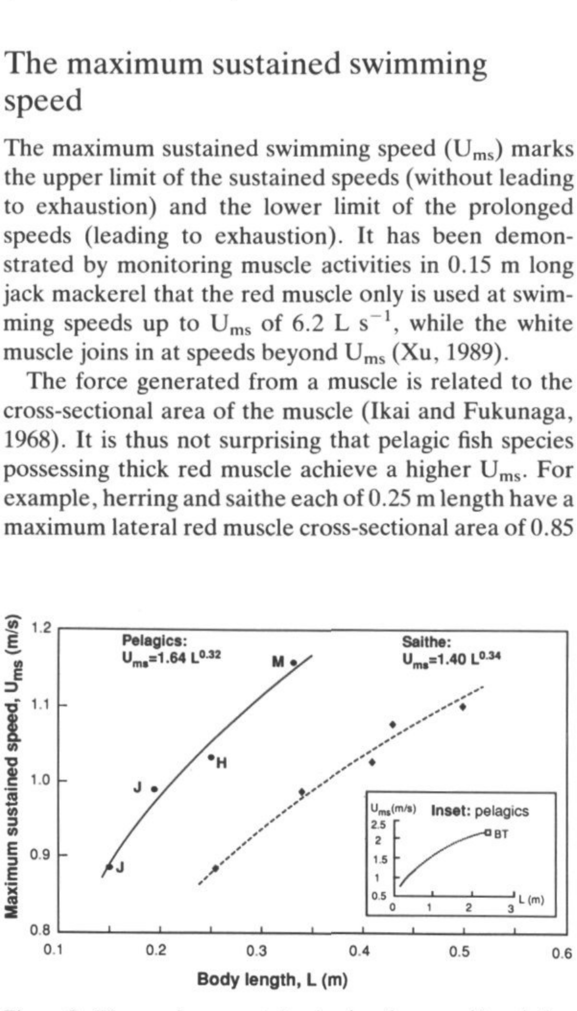

Figure 2. The maximum sustained swimming speed in relation to body length of pelagic species (solid curve) and demersal species (dashed curve). Letter symbols are: M – Atlantic mackerel, *Scomber scombrus*, 11.7°C, H – herring, *Clupea harengus*, 13.5°C (He and Wardle, 1988); and J – jack mackerel, *Trachurus japonicus*, 19°C (Xu, 1989). Solid diamonds: saithe, *Pollachius virens*, 14.4°C (He and Wardle, 1988). Inset: pelagic species; BT – bluetin tuna, *Thunnus thynnus*, of 2.44 m length with a predicted U_{ms} of 2.10 m^{-1} s (see text for explanation).

and 0.55 cm^2 respectively (He, 1986). Likewise, herring has a U_{ms} of 1.06 m s^{-1} compared with 0.89 m s^{-1} for saithe, both at around 14°C.

The maximum sustained swimming speed (U_{ms}, in m s^{-1}) increases with an increase in fish body length (L, in m) in both saithe and small pelagics (mackerel, herring, and jack mackerel) (Fig. 2), but U_{ms} is consistently lower in saithe. Bluefin tuna (pelagic species) can grow to more than 3 m in length. Bluefin tunas in farm cages with a mean length of 2.44 m swam at an average speed of 0.77 L s^{-1} or 1.88 m s^{-1} (Wardle *et al.*, 1989). Extrapolating the length to 2.44 m from the line for pelagic species, the predicted U_{ms} for 2.44 m tuna will be 2.10 m s^{-1} (Fig. 2: inset) or 0.86 L s^{-1}.

Endurance at prolonged swimming speeds

Endurance at prolonged swimming speeds has been measured by using the "fish wheel" (Bainbridge, 1960), swimming flumes (e.g. Beamish, 1966; He, 1991), a stationary annular tank (He and Wardle, 1988), and by observations at sea near fishing gears (Wardle, 1983). He and Wardle (1988) measured swimming speed and endurance of mackerel (see solid line Fig. 1), herring, and saithe in a 10 m diameter annular tank; it is particularly worth noting that these fish were induced to swim through still water by moving a projected visual pattern, imitating fish swimming in the mouth area of a towed trawl. Swimming at the same speed as the towed trawl at the mouth area is believed to be induced by moving netting panels. Measured endurance of commercial marine species is plotted against swimming speed in Figure 3. In all species swimming at prolonged speeds, endurance drops drastically as speed is increased.

Larger fish can swim longer at the same speed in m s^{-1} or they can swim faster at the same endurance. For example, a 0.50 m long saithe can swim for 30 min at 1.25 m s^{-1}, while a 0.25 m saithe can only swim for 2 min at the same speed of 1.25 m s^{-1} or can only swim at 0.95 m s^{-1} for the same endurance of 30 min (Fig. 3c). Pelagic species have a better endurance swimming ability. At 14°C, a herring of 0.25 cm can swim for over 15 min at 1.25 m s^{-1}, while a saithe of the same length can only sustain the same speed for 2 min.

Burst swimming speeds of marine fishes

Burst swimming speeds are difficult to measure, both in the laboratory and at sea. A large tank and a high-frame-rate camera with an accurate timer are essential equipment for recording high-speed movement. But the most difficult task is to make fish swim at their highest possible speed. A 10 × 5.4 × 1 m deep tank and a cine camera capable of filming at a frame rate up to 500 frames per second were used in mackerel burst swimming speed measurements utilizing mackerel escape behaviour when released into the large tank (Wardle and He, 1988). With this arrangement, U_{max} of 18 L s^{-1} or 5.5 m s^{-1} was measured in a 0.31 m long mackerel.

The maximum swimming speed (U_{max}) increases with fish body length (L) and water temperature, and varies among fish species. Figure 4 shows measured U_{max} (in m s^{-1}) of commercial marine fishes plotted against L (in m) with temperature values indicated in the legend when available. Notice that most fish have a U_{max} between 10 and 20 L s^{-1}. U_{max} of those species falling below 10 L s^{-1}, such as saithe and Pacific mackerel, are probably higher than the plotted values. Notice that the swimming speed of herring (HR in Fig. 4) of 4.61 m s^{-1} or 17.1 L

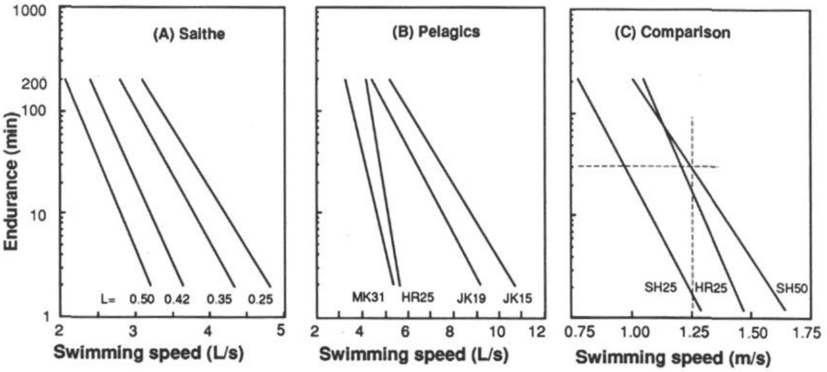

Figure 3. Swimming speed and endurance of marine fishes. (A) Demersal species: saithe, *Pollachius virens*, of different lengths (L, m) at 14.4°C (He and Wardle, 1988). (B) Pelagic species: MK31 – Atlantic mackerel, *Scomber scombrus*, 0.31 m long at 11.7°C, HR25 – herring, *Clupea harengus*, 0.25 m long at 13.5°C (He and Wardle, 1988), JK19 and JK15 – jack mackerel, *Trachurus japonicus*, 0.19 and 0.15 m long at 19°C (Xu, 1989). (C) Comparison of saithe (SH25) and herring (HR25), both 0.25 m long, and comparison of saithe 0.25 m (SH25) and 0.50 m (SH50) long. Dashed lines indicate endurance when swimming at 1.25 m s^{-1} (2.5 kt) and swimming speeds at endurance of 30 min for the three groups of fish. Pelagic species or larger fish have a better endurance swimming capability.

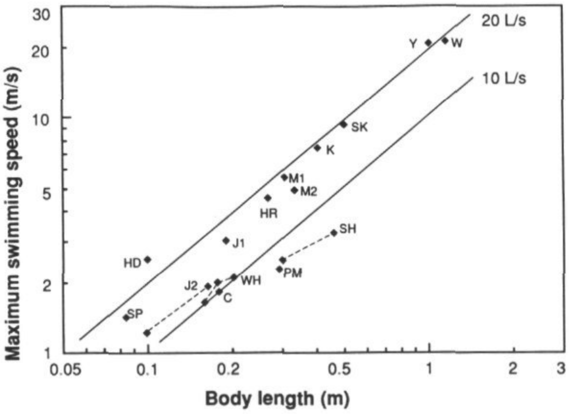

Figure 4. Maximum swimming speeds of marine fishes in relation to body length. Dashed lines link different lengths of the same species. Letter symbols, sources, and temperatures (when available) are: C – cod, *Gadus morhua*, 9.5–12°C (Blaxter and Dickson, 1959); HD – haddock, *Melanogrammus aeglefinus*, 12°C (Wardle, 1975); HR – herring, *Clupea harengus* (Misund, 1989); J1 – jack mackerel, *Trachurus japonicus*, 23°C (Xu, 1989); J2 – jack mackerel, *Trachurus symmetricus* (Hunter and Zweifel, 1971); K – kawakawa, *Euthunnus affinis*, 25°C (cited in Beamish, 1978); M1 – Atlantic mackerel, *Scomber scombrus*, 12°C (Wardle and He, 1988); M2 – Atlantic mackerel, *Scomber scombrus* (Zhou, 1985); PM – Pacific mackerel, *Scomber japonicus* (Hunter and Zweifel, 1971); SH – saithe, *Pollachius virens*, 10.8°C (He, 1986); SK – skipjack tuna, *Katsuwonus pelamis* (cited in Magnuson, 1978); SP – sprat, *Sprattus sprattus*, 12°C (Wardle, 1975); W – wahoo, *Acanthocybium solandrei*, >15°C (Walters and Fierstine, 1966); WH – whiting, *Gadus merlangus*, 9–13°C (Blaxter and Dickson, 1959); Y – yellowfin tuna, *Thunnus albacares* (Walters and Fierstine, 1966).

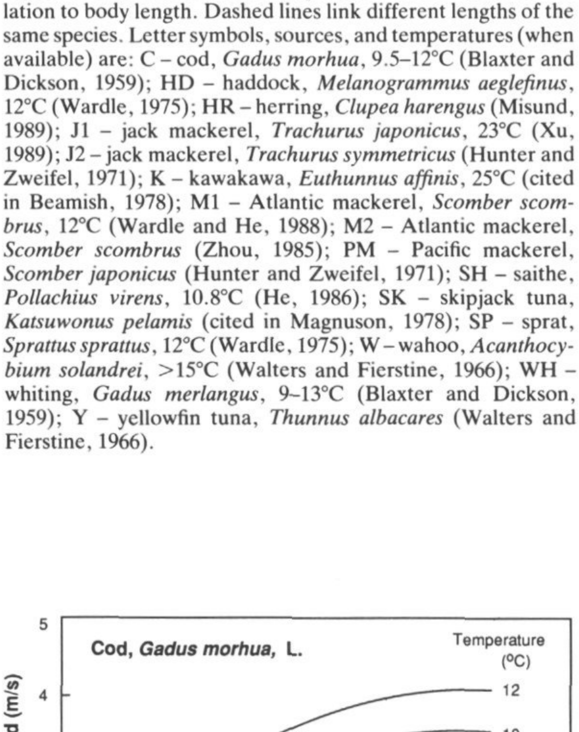

Figure 5. The maximum swimming speed of cod, *Gadus morhua*, in relation to body length and temperature as predicted from the measured muscle contraction time. Drawn from data given in Videler and Wardle (1991) with a stride length of 0.60 L.

s^{-1} is the speed of a herring school during purse seine operations measured by a scanning sonar sampled at 10 s intervals (Misund, 1989).

The maximum swimming speed can be predicted from the contraction time of the white muscle (which limits tail beat frequency, Wardle, 1975) and stride length (SL, distance travelled forward in one complete tail beat). Contraction time does not change among fish species, but varies with body length (Wardle, 1977), temperature (Wardle, 1980), and location of muscle along the body (Wardle, 1985). Stride length is species-specific; larger values are found in species with an efficient caudal fin and a low-drag streamlined body. The value of stride length varies between 0.60 and 1.04 L in marine fishes (Videler and Wardle, 1991). Scombroid fishes like mackerel and tuna have a well-streamlined body and a large caudal fin of high aspect ratio. For example, mackerel (SL=1.0 L, Wardle and He, 1988) will be able to swim 67% faster than cod (SL=0.60 L, Videler and Wardle, 1991) at the same tail beat frequency.

Effect of temperature on the swimming speeds of fish

All fish, except some large scombroids and large sharks, have a body temperature equal to the ambient water temperature which varies in time and space. Temperature has a profound impact on almost all aspects of fish physiology, including swimming performance.

There are no systematic, direct measurements of the maximum swimming speed at different temperatures. But measurements of white muscle contraction time indicate a higher maximum swimming speed in all species at higher temperatures. Figure 5 shows the maximum swimming speed of cod at temperatures between 2 and 12°C calculated from the measured muscle contraction time (Videler and Wardle, 1991). These same authors showed that fish can double their maximum swimming speed with a temperature increase of 10°C, i.e. a Q_{10} of 2. Higher temperature allows a higher maximum tail beat frequency (Wardle, 1980) and a higher power output from the white muscle (Johnston and Salamonski, 1984).

A reduction in temperature reduces swimming speed and endurance (Fig. 6). Typical temperatures for cod on the Newfoundland Grand Banks are between 0 and 5°C. Notice that a reduction in temperature from 5 to 0°C can cause a reduction in swimming speed from 1.05 m s^{-1} to 0.65 m s^{-1} for a swimming endurance of 30 min. Or if a fish has to swim at the same speed of 1 m s^{-1} (e.g. at the mouth of a towed trawl), the fish will be exhausted in 2 min at 0°C compared with 50 min at 5°C.

U_{ms} decreases with a drop in water temperature, especially at lower temperatures (Fig. 7). U_{ms} of cod at 0.8°C is only 0.42 m s^{-1} compared with 0.90 m s^{-1} at 8°C (0.35–0.42 m cod), a reduction of 54%. This decrease of

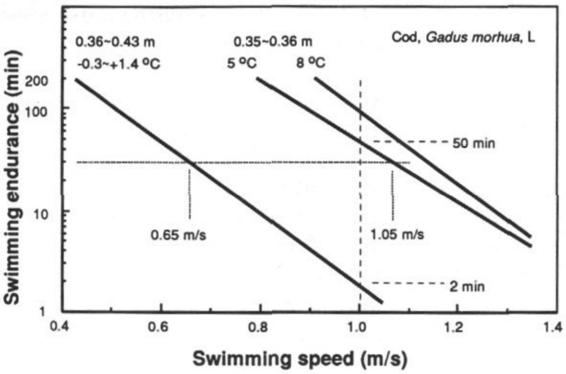

Figure 6. Swimming speed and endurance of cod, *Gadus morhua*, at different water temperatures from −0.3 to 8°C. Dotted lines indicate the swimming speed sustainable from an endurance of 30 min. Dashed lines indicate different endurance swimming at 1 m s^{-1}. Swimming speed and/or endurance decreases as temperature is reduced (redrawn from He, 1991).

U_{ms} in cod is comparable to a decrease in routine activity (by 75%), frequency of opercular movement (by 50%), feeding (by 58%), and growth rate (by 36%) for the same species when temperature is dropped from 8.3 to 0.6°C (Brown *et al.*, 1989), and in the maximum swimming speed (by 45%, see Fig. 5). Bottom and midwater temperature off Newfoundland can be as low as −1.8°C (He and Xu, 1992). Cod were observed by underwater video camera to swim around baited hooks at water temperatures as low as −1.2°C in fishing grounds, though the number of cod observed is very small compared with that at higher temperatures (He and Xu, 1992, unpublished). If the curve in Figure 7 is extended from +0.8 to −1.2°C, a predicted U_{ms} will only be 0.14 m s^{-1} (or 0.3 kt) for a 0.35 m long cod.

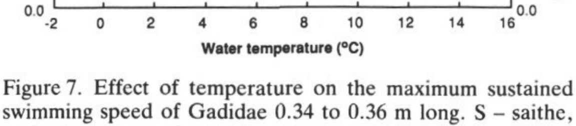

Figure 7. Effect of temperature on the maximum sustained swimming speed of Gadidae 0.34 to 0.36 m long. S – saithe, *Pollachius virens*, from He and Wardle (1988) and C – cod, *Gadus morhua*, from He (1991) and Beamish (1966). Solid symbols are measured data and the open symbol is the predicted value for the lowest temperature of −1.2°C as observed on the fishing grounds (He and Xu, 1992).

Differences in swimming speeds and endurance at different water temperatures influence the herding of fish by sweeps, the ability of fish to keep station with the trawl at the mouth area, and the escape of fish in the codend. All these temperature-related fish–trawl interactions can influence efficiency and selectivity of trawls. This is especially important when the trawl is used as a sampling tool for stock assessment.

Fish swimming and mesh selectivity of trawl codend

Selectivity of otter trawls occurs mainly in three areas: during herding by sweeps (or bridles); during swimming with the trawl at the mouth area; and mesh selection at the codend. All these are related to, among other things, the swimming behaviour and swimming capacity of fish. Herding by sweeps and exhaustion of fish at the mouth area in relation to swimming speed of fish have been discussed by Foster *et al.* (1981), and more recently by Wardle (1983, 1986, 1989). Codend selectivity is defined as the proportion of fish retained in the codend as catch, in relation to the total number of fish arrived at the codend prior to any escapement. Codend mesh size, mesh shape, and codend riggings are believed to affect the size selectivity of the codend (Robertson, 1989). However, the effect of towing speed and swimming ability of fish in relation to size selectivity in the codend has not been investigated. Here a model is developed to explore how the swimming ability of fish affects codend mesh selection.

It is assumed that a fish has escaped from the codend if the fish has swum a distance X_L (shoulder length) so that its shoulder B1-B1′ (the position of the maximum body height) moved to B2-B2′ in the time period when the mesh moved a distance of Mu_2-H (M is mesh size, u_2 the vertical hanging ratio and H the maximum body height) from the position of A1-A1′ to A2-A2′ (Fig. 8). Thus, the swimming speed required (U_r) to escape from the codend of a trawl towed at speed U_t is: $U_r = U_t K_x/(Mu_2/L-K_h)$, where $K_x = X_L/L$, $K_h = H/L$. Whether a fish can escape from the codend is determined by the swimming speed required and the swimming speed achievable. As escape through the mesh occurs in a short time period, the maximum swimming speed is considered. From the above formulae, it can be seen that U_r is related to the size of mesh, fish length and body geometry (K_x and K_h), and the towing speed.

Swimming speeds required to escape from the codends of different mesh sizes towed at 3.5 knots (Fig. 9a) and from 130 mm mesh towed at different speeds (Fig. 9b) are calculated from the above formulae for cod (assuming K_x=0.3, and K_h=0.2). Plotted in the same graphs are the maximum swimming speed of cod at three different water temperatures from Figure 5. Those combinations of speed, length, and mesh size above the

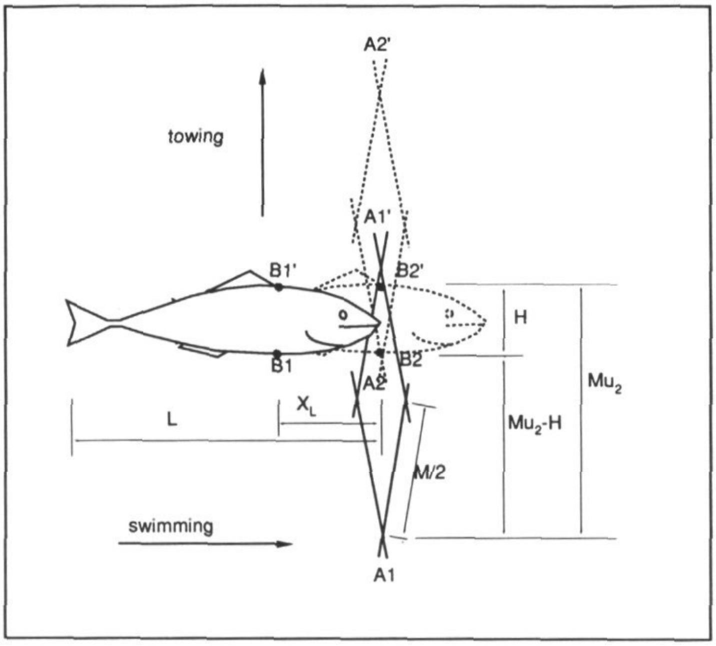

Figure 8. Schematic drawing of fish escapement through a codend mesh. Solid drawing is at time 1 and dashed drawing at time 2. B1–B1′ (or B2–B2′) is the shoulder position. X_L is the shoulder length and H the maximum body height. M is the mesh size (M/2 mesh bar length) and u_2 vertical hanging ratio. The swimming speed required for a fish to escape from the mesh is determined by whether the shoulder B1–B1′ can move to B2–B2′ just before the mesh moves from A1–A1′ to A2–A2′.

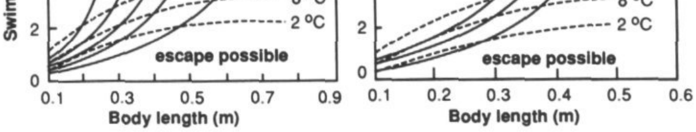

Figure 9. Swimming speed required (solid curves) to escape through the codend and the maximum swimming speed (dashed lines, from Fig. 5) of cod at different temperatures. (A) Different codend mesh sizes towed at 1.80 m s^{-1} (3.5 kt); (B) 130 mm codend mesh towed at different speeds. Those combinations of speed, length, and mesh size above the maximum speed line at a particular temperature indicate the area where escape is impossible.

maximum speed line at a particular temperature indicate the area where escape is impossible, and conversely. It can be seen that larger mesh sizes and slower towing speeds allow a wider range of fish to escape from the codend. Higher temperature increases swimming speed of fish and facilitates escape through codend meshes. For example, at 8°C, a 0.55 m cod will be able to escape a 200 mm mesh, while only fish equal to or less than 0.20 m can escape a 110 mm mesh when towed at 3.5 knots (Fig. 9a). Slower towing speeds will allow larger fish to escape. At 8°C, a 0.35 m fish will be able to escape a 130 mm mesh towed at 2.5 knots, but only fish below 0.20 m can escape the same sized mesh towed at 4.5 knots (Fig. 9b). In the case of cod, when water temperature drops to around 0°C, almost no fish will be able to escape actively through any practical codend meshes.

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Consequences of fish behaviour for stock assessment

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Fréon, P., Gerlotto, F., and Misund, O. A. 1993. Consequences of fish behaviour for stock assessment. – ICES mar. Sci. Symp., 196: 190–195.

The influence of fish behaviour on the most common stock assessment methods is reviewed. Fish behaviour may be divided into four major groups: habitat selection, aggregation pattern, avoidance reactions, and learning. Examples of temperate and tropical species are presented.

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Introduction

Indirect stock assessment techniques have improved considerably through the development of population dynamics, and the use of computers and adequate statistics have increased their precision. Direct stock assessment methods such as fisheries acoustics are still improving, largely because of benefits from technological progress.

Although fish behaviour is not directly represented through parameters in the stock assessment methods, there is an increasing awareness that behaviour is a major limiting factor in the accuracy of abundance estimates. To illustrate the reasons behind this awareness, we review how fish behaviour, grouped into habitat selection, aggregation patterns, avoidance reactions and learning, may influence the most common stock assessment methods (Table 1).

Habitat selection

Habitat selection is one of the functional behavioural systems for adult fish (Huntingford, 1986). Many fishes change habitat diurnally, seasonally, and some from year to year. Such changes in fish distribution can affect stock assessment.

Availability

A difficulty for direct stock assessment arises when fish occupy habitats unavailable to sampling gears. Acoustic assessment requires that fish be distributed from a few metres below the surface to a small distance off the bottom (Mitson, 1983). Several economically important species such as cod (*Gadus morhua*) and walleye pollock (*Theragra chalcogramma*) live semipelagically, and in such cases a combination of acoustic and trawl surveys is applied (Godø, 1990; Wespestad and Megrey, 1990). A substantial difficulty for this approach is that semipelagic species sometimes choose to live mostly demersally or pelagically (Godø, 1990). Similarly, species usually living pelagically, such as herring (*Clupea harengus*), may distribute themselves in some instances so close to the surface or bottom as to be inaccessible to acoustic assessment (Jakobsson, 1983).

Short-term variation

Short-term variation in fish distribution makes it impossible to obtain the same observation in the same place at two different instants. Gerlotto and Petitgas (1991) observed that the biomass estimated by echo integration could double between two successive recordings of the same transect owing to movements of schools. Apart from generating a random process in the data set, such variability makes use of geostatistics difficult owing to the presence of highly different density values at the same geographical point. It may also put a limit on increasing the precision of an estimate by higher sampling intensity (Aglen, 1989). When the variability between two neighbouring transects is the same as that between two repetitions of a transect, no benefit can be expected by further decreasing the intertransect distance.

Table 1. Relative importance of four behavioural patterns on four categories of stock assessment approach.

	Stock assessment method			
Behavioural pattern	Cohort analysis, VPA, etc.	Surplus production models	Trawl survey	Acoustic survey
Habitat Choice				
Short term	0	0	+ or −	++ or −−
Diurnal	0	0*	++ or −−	++ or −−
Seasonal	0	0*	++ or −−	+ or −
Yearly	+ or −	+++ or −−−	++ or −−	0
Aggregation	0	+++ or −−−	++ or −−	++ or −−
Avoidance	0	0	−−−	−−
Learning	−(?)	−(?)	−(?)	0

0 = no influence of behaviour.
+, ++, +++ = increasing risk of over-estimation.
−, −−, −−− = increasing risk of under-estimation.
* except if interannual changes in the fishing pattern are not taken into account.
(?) importance not clearly assessed.

Data gathered by trawl surveys generally also provide a high variability (Ulltang, 1977) which may partially result from horizontal or vertical displacement of the biomass. Repeated trawling at the same place may suggest varying influence of factors such as temperature (Rijavec, 1971), internal waves (Caverivière, 1982), and light intensity. Flatfishes may take advantage of tidal currents for horizontal migration by moving up in the water column when the flow direction is favourable (Arnold *et al.*, 1990), and the catchability may change accordingly.

Diurnal variation

In coastal areas, pelagic fish often display diurnal horizontal migrations. Menhaden (*Brevoortia patronus*) move inshore and on the surface at night, but are found offshore and close to the bottom during the day (Kemmerer, 1980). Gerlotto and Petitgas (1991) observed that fish were present in the central part of the Gulf of Cariaco (Venezuela) by night and near the coast by day.

Clupeoids usually perform diurnal vertical migrations that seem mainly related to a light intensity preferendum (Blaxter and Hunter, 1982). Carangids of tropical areas also undertake vertical migrations, but this pattern is not constant and changes according to age and region (Boély and Fréon, 1979). In the Senegalese purse seine fisheries some species are caught during the day, others at night, and the catch per unit of effort (c.p.u.e.) therefore gives different abundance indices for different categories (day, night, day + night) of computation.

The proportion of species studied may vary diurnally as some demersal ones become pelagic by night. This change in behaviour may introduce biases to results from direct methods when sampling is conducted during both day and night (Engås, 1991). Vertical movements may affect the swimbladder volume, especially in physostomatous fish, and may have an impact on target strength (Blaxter and Batty, 1990).

Seasonal variation

Surveys are usually conducted during the same time of year to avoid bias arising from seasonal variation in fish distribution. If fish are migrating, bias may occur in acoustic estimates, but this can be corrected by taking account of the mean migration speed (MacLennan and Simmonds, 1992).

Interannual variability

Dramatic fluctuations in biomass may change the area occupied by pelagic stocks (e.g. of clupeoids) by a factor of 10 or more. For demersal stocks, the population explosion may be associated with a complete change of habitat. For instance, along the West African coast, *Balistes carolinensis* was until 1971 considered to be a not very abundant demersal species. Then this species started to colonize the pelagic system during the first years of its life, and in 8 years its biomass increased to 10^6 tons (Caverivière *et al.*, 1980), although it is now declining to the level that prevailed before 1970. The demographic explosion of *Macroramphosus* sp. off Morocco in the 1970s presented a similar pattern (Belvèze, 1991). None of these stocks was exploited, and catch-based methods were obviously not adapted for assessment.

Social aggregation

Fish can distribute and behave individually, assemble socially in shoals, or swim synchronized and polarized in schools (Pitcher, 1983) These behaviour patterns have a significant influence on sampling.

Density distribution

The aggregative behaviour of fish induces a large dispersion and skewness in the distribution function of echo integration data. This is especially evident when the fish assessed are schooling (Aglen, 1989). The confidence limits of biomass estimates obtained with classical statistics may therefore be large, but the first two moments (mean and variance) of the distribution function still seem finite, and the central limit theorem may apply. However, cases exist where the distribution function of the data sampled does not have these properties. In such cases an increase in sampling rate has a limited effect on the precision of the estimate. There are examples of acoustic surveys in tropical areas that resemble a Pareto distribution (Lévy, 1925) with infinite variance. In such cases the arithmetic mean does not give a good estimate of the population.

Buerkle and Stephenson (1990) found large variations in biomass estimates from repeated night-time acoustic surveys of herring in Chedabucto Bay, Nova Scotia, Canada, which they claimed were caused by great dynamics in the aggregations. Aglen (1989) showed that variability in acoustic survey estimates decreases with increasing degree of coverage. Vilhjálmsson *et al.* (1983) and Strømme and Sætersdal (1987) demonstrated good replicability of repeated surveys in northern and tropical areas, respectively.

Target strength

Social aggregation also affects the orientation of fish, resulting in a higher average target strength when schooling than when shoaling (Foote, 1980). A diurnal variation in target strength has been observed for caged cod, herring, and mackerel (*Scomber scombrus*) (MacLennan, 1990). The variation is especially large (about 5 dB) for mackerel owing to hydrodynamic constraints on this swimbladderless fish (He and Wardle, 1986). Therefore, different target strength values should be applied for daytime schooling and night-time shoaling, but the validity of cage measurement may be questioned as fish may polarize by day as well as by night when affected by survey vessels. However, for walleye pollock the *in situ* target strength was found to be 3 dB lower by night than by day (Traynor and Williamson, 1983).

Acoustic shadowing

The echo integration method is linear (Foote, 1983). However, in fish aggregations with a large vertical extent, substantial extinction of the sound energy emitted from an acoustic transducer can occur (Røttingen, 1976). By recording the attenuation in the bottom echo as a function of the vertical extent of herring shoals in a Norwegian fjord, Toresen (1991) fitted equations to correct the fish density estimates for extinction. A solution to correct for extinction in aggregations with varying density is proposed by Foote (1990).

Catchability

Changes in stock abundance of pelagic species often occur without noticeable changes in catchability or with changes inversely proportional to the area occupied by the stock (Ulltang, 1976; Shelton and Armstrong, 1983). On the other hand changes in catchability may occur without change in abundance when long-term changes in the environment influence the aggregation pattern (Mangel and Breder, 1985). For pelagic stocks exploited by purse seiners, the usual c.p.u.e. is computed using the time spent searching for schools. Evidently in such cases c.p.u.e. is not a good abundance index. The mean catch per set in purse seine fisheries could be considered as an abundance index under the assumptions that the mean school size is related to the stock abundance and that the catch per set is proportional to the school size. These assumptions seem to be met in the Senegalese sardinella fisheries after the data set is filtered (Fréon, 1989).

Vessel avoidance

Modern survey vessels generate substantial low-frequency noise that has peak energy within the hearing range of teleosts (Mitson, 1989). This noise may elicit avoidance reactions that may drastically reduce the fish density that can be recorded by echo integration units underneath survey vessels (Olsen *et al.*, 1983). Recordings from a small independent vessel when a survey vessel passes close to it have shown density reductions ranging from 40% to 90% for shoaling herring in Norwegian fjords, and cod and polar cod (*Boreogadus saida*) in the Barents Sea (Olsen, 1990). Other studies on cod and haddock (*Melanogrammus aeglefinus*) revealed no, or just weak, avoidance reactions to survey vessels running at normal cruising speeds (Ona and Godø, 1990). Similar studies on tropical clupeoid species in shallow water showed no reduction in fish density during passage of small survey vessels, either when sailing or when motor driven (Fréon *et al.*, 1990). Schools of *Sardinella aurita* off Venezuela avoided vertically, but only in the upper 20 m, when a medium-sized survey vessel passed over them, and this resulted only in little underestimation of the density as the average tilt angle during the dive was estimated to be less than 10° (Gerlotto and Fréon, 1992). Recordings by sonar show about 20% underestimation of fish density owing to horizontal avoidance by herring schools in the North Sea, and no avoidance of spawning migrating capelin schools in the Barents Sea (Misund 1991; Misund *et al.*, 1992). This indicates that vessel avoidance reactions may vary substantially, and Neproshin (1979) argued that Pacific mackerel (*Pneumatophor-*

us japonicus) avoids most when well fed and swimming in schools, less when shoaling and feeding, and even less when occurring in low-temperature water. Herring seem to react less the better the sound propagation conditions, but more strongly when on spawning migration than when feeding or on feeding migration (Misund, 1991).

At night, avoidance may occur as a response to visual stimulation by the vessel's lights. Lévénez *et al.* (1990) observed vertical avoidance of tropical clupeoids off Venezuela during new moon when running a survey vessel with a 500 W light on the bridge, but the mean echo integral was the same with the lamp on or off. In a similar experiment, Gerlotto *et al.* (1990) observed no vertical avoidance, but found indications of species- or size-dependent horizontal avoidance when the lamp was on.

Vessel avoidance reactions may increase during trawling, as observed for cod and haddock (Ona and Godø, 1990), and such reactions may even make trawl sampling of schooling species such as herring difficult (Misund and Aglen, 1992). Similarly, vessel avoidance reactions may cause difficulties in combining the results from swept area and echo integration estimates of semipelagic fish. However, for Pacific whiting (*Merluccius productus*), Nunnallee (1991) observed no change in vertical distribution when a trawler passed over (but a strong avoidance of the trawl).

Fishing gear avoidance

A basic assumption of assessment methods is that samples by trawl are representative of the populations recorded. There is increasing evidence that this sampling principle is an oversimplification, as gear avoidance reactions change according to species and age of the fish (Engås, 1991; Godø, 1990). Main and Sangster (1981) observed that cod search towards the bottom when approached by a bottom trawl, haddock rise and may escape over the headline in substantial numbers, and whiting (*Merlangius merlangus*) tend to aggregate more in the middle of the trawl opening. The reactions of cod differ among size groups, so that the smallest fish escape under the ground gear and are grossly underestimated in the catches (Godø, 1990; Engås, 1991).

Gear avoidance seems mainly elicited by visual stimuli, and the reactions decrease at night-time (Glass and Wardle, 1989). However, endogenous rhythms may also be of importance because the catchability of demersal fish in West Africa increases suddenly before dawn, without a change in light intensity (Baudin-Laurencin, 1967).

Learning

Like all animal groups, fishes are able to adapt their behaviour towards fishing gear through learning (Fernø and Huse, 1983). Pyanov (1992) argues that "one-trial learning" may exist because tagged fish were not caught any more by the trawl gear that caught them initially. Similarly, Soria *et al.* (this volume) showed that under certain conditions, experienced clupeoids can transmit avoidance behaviour to a naive school. This indicates that fish are able to learn, allowing them to avoid the fishing gears after having escaped once. Moreover, fish can retain their learned experience for months (Coble *et al.*, 1985).

The consequences of learning may be a long-term decrease in efficiency of the fishing gears, and biases in the use of c.p.u.e. as indices of abundance. If the oldest fish are more experienced with fishing gear, their fishing mortality may be lower than expected. This will affect VPA and cohort analysis because the fishing mortality of the oldest age groups must be estimated *a priori*, and the corresponding error in this estimation will propagate in the vector of mortality.

Conclusion

All stock assessment methods considered here may suffer biases owing to fish behaviour (Table 1). Cohort analysis must be tuned by at least one parameter (fishing effort, recruitment, c.p.u.e.) estimated by other methods, and may thereby be biased. Stock assessments based on fishery-independent, *in situ* observations are becoming increasingly important, and on such methods (fishery acoustics, trawl surveys) variations in natural fish behavioural patterns and in reactions to vessels and fishing gear may have large impacts. In order to understand the determinism of natural behavioural patterns and avoidance reactions, we argue that fish behaviour research must be escalated with special attention to *in situ* studies, as there is a large potential for increasing the accuracy of stock assessment methods through a better knowledge of fish behaviour.

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Comparison of efficiency of standard and experimental juvenile gadoid sampling trawls

O. R. Godø, J. W. Valdemarsen, and A. Engås

Godø, O. R., Valdemarsen, J. W., and Engås, A. 1993. Comparison of efficiency of standard and experimental juvenile gadoid sampling trawls. – ICES mar. Sci. Symp., 196: 196–201.

Annual trawl surveys to estimate relative abundance of 0-group cod in the Barents Sea have been conducted since 1965. Indices of abundance calculated from survey results have been used as an initial indication of year-class strength. Low correlation between the 0-group index and year-class strength observed subsequently, however, reduces the prognostic value of the indices. In this paper, results from experiments with a new sampling trawl are presented and compared with data from the standard trawl. We investigated the possibility that this low correlation could be partially attributed to the performance and efficiency of the standard sampling trawl and sampling procedures. The results indicate that variation in geometry and size selectivity of the standard sampling trawl may cause considerable errors in the indices calculated. Size-specific depth distribution of the juveniles and trawl selectivity may cause variability among areas and years, and this may be confounded by interannual variation in growth rates of juveniles. Studies of effects of fish behaviour in the propeller wake revealed no effect of avoidance during sampling in the surface layer.

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Introduction

Surveys to estimate relative abundance of 0-group Northeast Arctic cod have been carried out in August–September each year since 1965 (Anon, 1991a). The indices of abundance obtained from this work have been used as a first indication of year-class strength. The time series of indices is used to tune recruitment estimates in the assessment (Anon., 1991b). There was a good relationship between the 0-group indices and recruitment at age 3 up to the mid-1980s (Randa, 1984). Even though the 1984–1986 year classes appeared to be strong in the 0-group surveys, recruitment at age 3 was much lower than expected (Anon., 1991b).

Quantitative analyses of abundance of pelagic gadoids demand sampling with known or equal efficiency at different depths and for the range of sizes and species encountered. The problems associated with analysis of vertical distribution and migration of pelagic gadoids are summarized by Neilson and Perry (1990). Also, estimation of mortality during the pelagic phase has been based on abundance estimates from trawl surveys (Campana *et al.*, 1989; Sundby *et al.*, 1989). The current studies focus on changes in sampling gear which may improve the quantitative assessment of pelagic gadoids in the Barents Sea.

The 0-group survey demands a substantial effort in order to cover the distribution area of the juveniles in the Barents Sea–Svalbard area (Anon., 1991a). In the period 1977–1991 an additional survey was carried out in June and July. At this time the postlarvae cover a smaller area than in August and September (Sundby *et al.*, 1989). If juvenile mortality between the two surveys is relatively constant from year to year, the earlier postlarvae survey should be more cost effective and should also give a less variable index with equal effort. The two surveys use similar sampling gear and procedures. Inconsistency between the indices of abundance from the two surveys may be caused by several factors. The more important are related to (a) *sampling gear selectivity and efficiency* such as the appropriateness of the mesh size relative to the fish size, (b) *sampling procedures in relation to the natural behaviour of the postlarvae and 0-group* such as vertical distribution, and (c) *fish avoidance in relation to the sampling gear* through escape behaviour. In this paper we report the results of experiments with a new sampling gear that were designed to elucidate these problems in relation to the two surveys.

Material and methods

Experiments with the standard larvae trawl and a new triple sampling gear were conducted off the Finnmark coast in August 1991 with RV "Michael Sars" (47 m LOA – 1500 hp).

The standard sampling trawl (ST) is a four panel, 16 fathoms capelin trawl with 200 meshes in front and 20 mm in the 40 mm long codend (Fig. 1). A 10 mm inside liner covered 4 m of the rear part of the codend. The trawl was rigged with 120 m bridles and 6 m^2 (1500 kg) WACO doors. Six plastic surface floats were arranged along the headline of the trawl to facilitate surface trawling.

The experimental gear (ET) consists of three equal trawls (Fig. 2), mounted together to constitute a starboard (S), centre (C), and port (P) trawl. Rigging is illustrated in Figure 3. The gear was spread with 2 m^2 Süberkrüb doors connected to the outer wings of the S and P trawls with 50 m bridles. The inner warps (see Fig. 3) were wound onto the trawl drum. Two plastic surface floats were fixed in front of each door to keep them at constant depth (5 m) during surface trawling. During surface hauls, the position of the trawl in relation to the propeller wake could be seen from the position of the plastic floats. When trawling at 30 m depth, the doors were operated without floats, and two 80 kg weights were attached at the conjunction points of the inner sweeps (Fig. 3). The gear was deployed so that the centre trawl was kept as close as possible to the wake of the propeller.

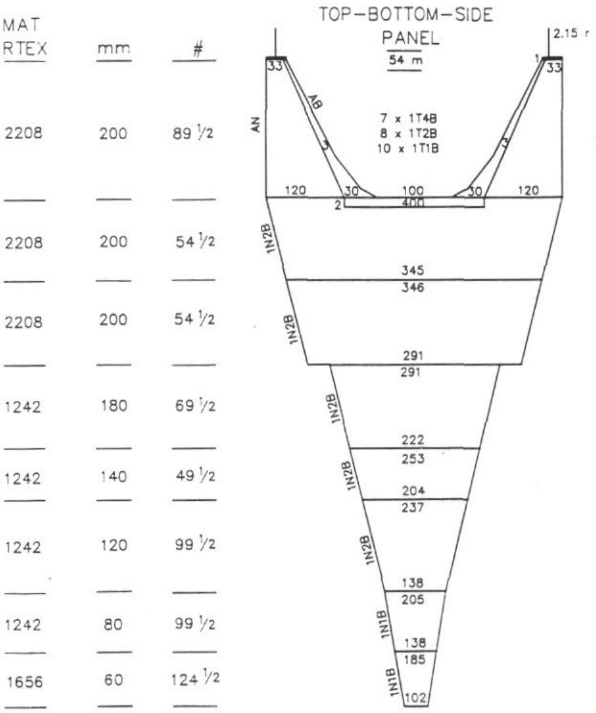

Figure 1. The standard pelagic sampling trawl.

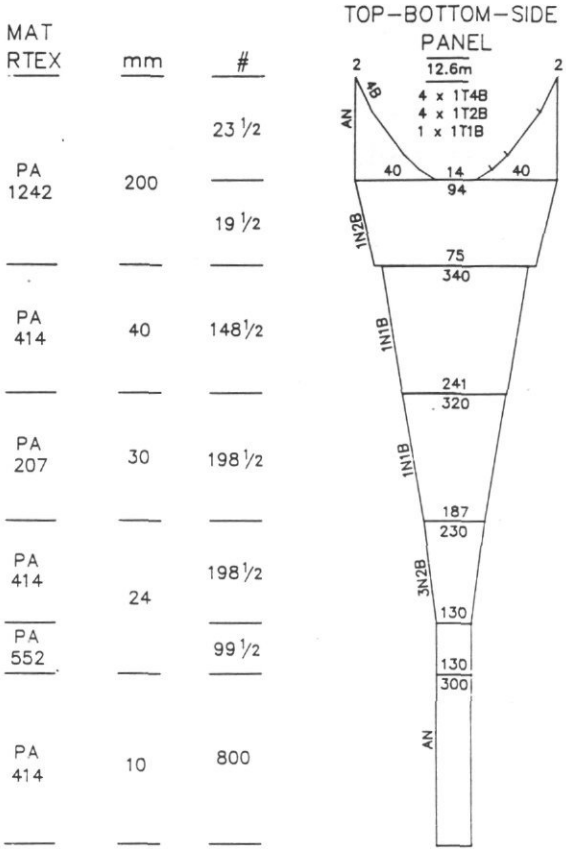

Figure 2. The experimental trawl.

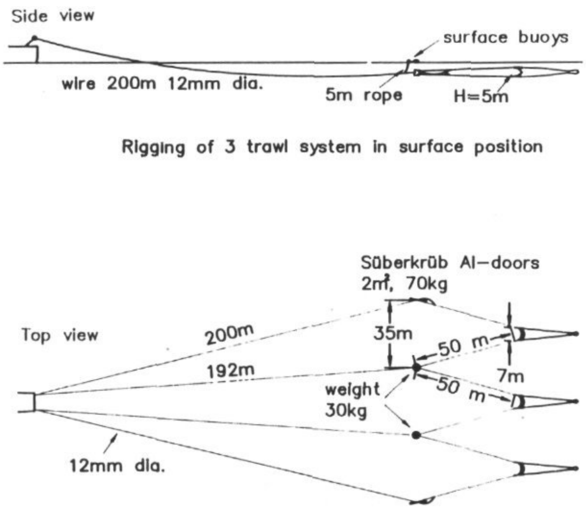

Figure 3. Rigging of the experimental trawl.

Selectivity and efficiency of the standard and experimental trawls were compared in a trawling experiment, which consisted of 18 hauls with the ET followed by six hauls with the ST in the same area.

If the vertical distribution of 0-group cod is size-dependent, and/or diurnal vertical migrations occur, then a considerable size selection of the sampling gear is likely and this will require a more sophisticated approach to the calculation of abundance indices. This problem was studied by comparing catches from the two gears at the surface and at 30 m depth.

Ona (1989) suggested that fish avoidance in the propeller wake could represent a considerable bias in the current 0-group survey procedures. He also proposed an arrangement with two trawls similar to the experimental gear to study the problem. If avoidance were to occur, the centre bag catch in our experiment would be expected to be affected more than the others.

Trawl geometry and performance were monitored during all hauls by acoustic trawl instrumentation (SCANMAR height and spread sensors). Trawl geometry and performance of the experimental gear were observed with a portable echo sounder and a Simrad FS3300 trawl sonar mounted on a rubber boat during the initial trials. During the surface hauls the geometry could also be visually controlled. Trawling depth during the deep hauls was observed with a Simrad cable netsonde mounted on the headline of the standard trawl, and the headline of the central experimental trawl was equipped with a depth sensor. During a standard haul the ST was towed for 30 min at 3 knots (as measured by Doppler log). The ET was towed for 30 min at a somewhat slower towing speed (2.5–3.0 knots).

For most catches, length measurements were taken for all cod. When catches exceeded several hundred individuals, measurements were taken from a representative subsample. The fish were measured to the nearest mm below. In the presentation, length groups of 5 mm are used, e.g. length group 22.5 represents fish of length 20–24 mm.

Changes in the length composition obtained from the different trawls were studied by comparing mean lengths with their standard errors. As the number of hauls is small and the coefficient of variation is large, jackknife estimates of the mean lengths and standard errors were used (Cochran, 1977; Effron and Gong, 1983), as done by Godø *et al.* (1990).

Results

Trawl geometry and performance

During surface hauls with the standard trawl (ST) the floats were seen on the surface, while the headlines of the experimental trawls were at 5 m during surface hauls. The spread of the experimental trawl was the same at the surface and at 30 m depth. The individual bags had a diameter of approximately 6 m, and hence covered an area of about 30 m^2. The standard trawl spread increased from about 9 m at the surface to 15 m at 30 m (Table 1). The vertical opening decreased from 32 m to 20 m for the same increase in towing depth so that the area covered by the standard trawl opening was approximately 300 m^2 at both depths. Trawl geometry observations between the centre of the headline and codend showed a netting angle of 14°. The trawl circumference gradually changed from elliptical to circular as shown in Figure 4.

Table 1. Trawl height (m) and wing spread (m) of the standard trawl (ST) and the experimental gear (ET) during trawling. Area open (m^2) was measured with trawl sonar.

Towing depth	Trawl height		Wing spread		Area open	
	ST	ET	ST	ET	ST	ET
Surface	32	6	9	10	300	30
30 m	20	6	15	10	300	30

Selectivity and efficiency

In this analysis all catches of the experimental trawl were adjusted to compare the area covered by the mouth of the standard trawl, i.e. the average catches from the three bags were multiplied by 10 and adjusted to the standard tow distance of 1.5 nautical miles.

At the surface the length distributions of the two trawls were markedly different (Fig. 5a). The average fish lengths from the experimental and standard trawls (Table 2) were significantly different. While the catch of the experimental trawl mainly consisted of fish less than

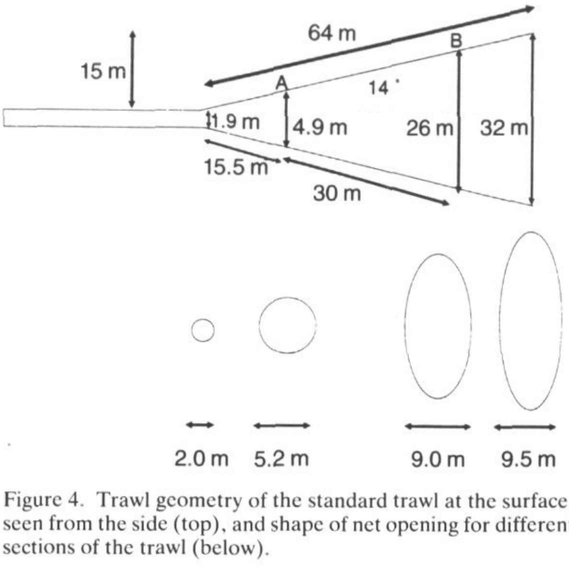

Figure 4. Trawl geometry of the standard trawl at the surface, seen from the side (top), and shape of net opening for different sections of the trawl (below).

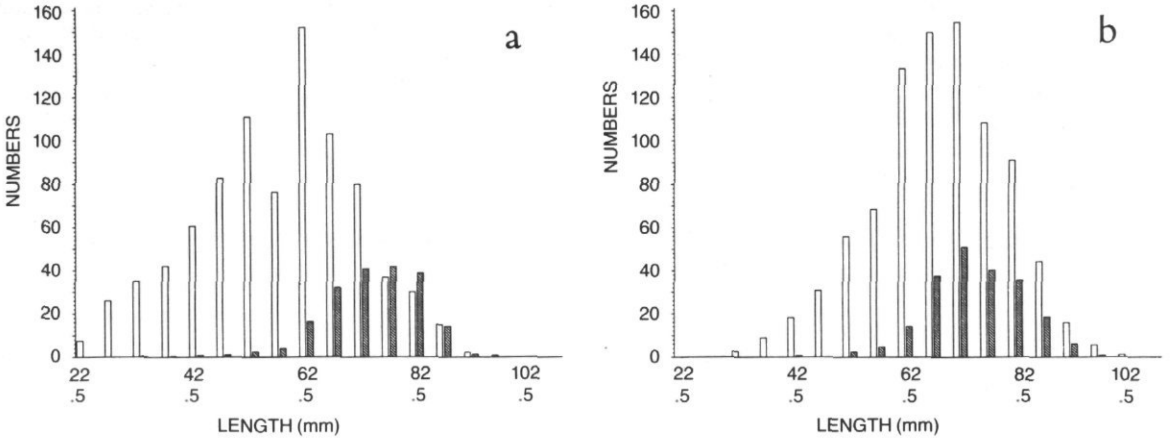

Figure 5. Length frequency distributions of 0-group cod at the surface (A) and 30 m (B), from the standard trawl (hatched columns) and experimental trawl (open columns).

65 mm, fish of these size groups were poorly represented in the standard trawl catch. The length distributions from catches at 30 m were more similar (Fig. 5b). The lower abundance or absence of small individuals in the standard trawl was still apparent, but the mean lengths (Table 2) were not significantly different.

Total catches at 30 m depth from the ET were higher than from the ST for all sizes of fish (Fig. 5b). At the surface the situation was similar for fish less than 65 mm, whereas the opposite occurred for larger fish (Fig. 5a). The experimental trawl appears to be more efficient for all sizes of fish at both depths, except for the largest 0-group fish at the surface.

Natural behaviour

The standard trawl results indicate no significant size-dependent vertical distribution (Fig. 5, Table 2). The ET results, in contrast, indicate substantial depth-specific differences in size composition: the smallest individuals were found at the surface (Fig. 5, Table 2).

Table 2. Estimated population mean length (mm) with standard error (s.e.) of cod for the different trawls and depths. ET-s, ET-c and ET-p are starboard, centre, and port bag respectively of the experimental trawl; ST denotes the standard trawl.

Gear	Depth	Mean length	s.e.
ST	Surface	74.3	0.82
ST	30 m	75.0	1.14
ET–s	Surface	54.7	8.10
ET–c	Surface	59.8	2.64
ET–p	Surface	56.0	4.80
ET–s	30 m	71.6	1.84
ET–c	30 m	71.3	5.09
ET–p	30 m	67.1	2.95

At the latitude of the experimental area (71°N), complete darkness does not occur in August. The sun is below the horizon for about 5 h, from 1830 to 2320 GMT. No night hauls were carried out with the ST and only four with the ET. There is a vague tendency for a smaller difference in mean length between surface and 30 m hauls at time intervals 1600 and 2000 (Fig. 6), caused by an increase in the length range of individuals caught at the surface. This may indicate that the larger individuals stay deep during the day but spread through the water column and mix with the smaller 0-group fish near the surface during night-time.

Avoidance

There was a big difference in the catch rates of the individual bags of the ET in different hauls (Figs. 7a, b). There is no indication of an avoidance reaction at the surface. In fact the average centre bag catch (113) was higher than the average catch from the other two bags (72), but the difference was not significant (*t*-test, $p = 0.34$). At 30 m the average centre bag catch was the lowest, but also here the difference was not significant (*t*-test, $p = 0.34$).

ET and ST catches at 30 m yielded similar length distributions (Fig. 5). At the surface, larger individuals were apparently caught more efficiently by the ST while 0-group fish smaller than 65 mm were caught much more efficiently by the ET. Owing to the much smaller size of the ET, this effect could have been caused by a minor avoidance reaction of the largest individuals.

Discussion

Most commercial trawl designs exploit the ability and the tendency of fish to avoid an approaching net, and so herd fish into the codend by using large-meshed netting

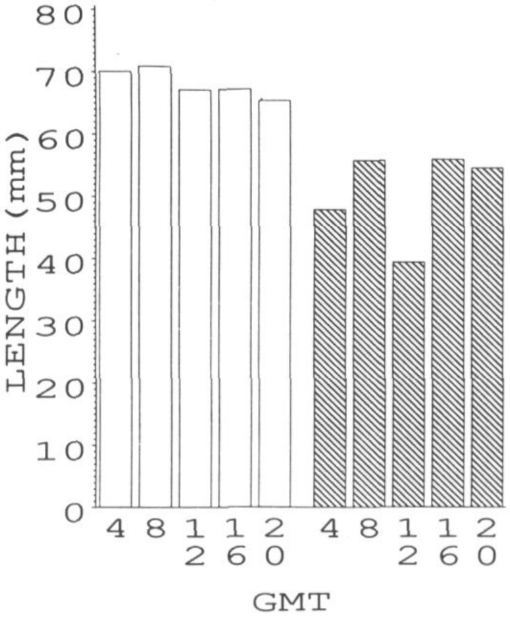

Figure 6. Mean length of 0-group cod in the experimental trawl catches from 5 m (hatched columns) and 30 m (open columns) in four-hour intervals (x-axis: Greenwich mean time).

in the front sections. When the goal of trawling is to obtain representative samples of the pelagic stages of juvenile gadoids, the low but still varying swimming capacity of these individuals has to be considered. Larvae at the surface need to dive 15 m to be caught by the ST (Fig. 4). If the avoidance response starts at the passage of the trawl headline, a diving speed of 38 cm s^{-1} for 40 s is necessary for larvae to be herded into the codend, otherwise they would be filtered through the meshes. In reality larvae probably will avoid at an angle different from 90° to the surface, and hence a swimming speed exceeding 38 cm s^{-1} is necessary, which is far greater than what can be expected for fish of this size (Wardle, 1977). In contrast, 120 mm fish, which also are frequently caught in the 0-group surveys, may not only be better herded by the large-mesh netting, but may also be able to react to ship trawling noise and start an avoidance reaction ahead of the trawl.

The very low catching efficiency of the ST, compared with the ET, for fish smaller than 60 mm at the surface indicates that these individuals are concentrated in the upper 15 m and that insignificant herding occurs, i.e. they are lost through the big meshes of the ST. Average length of 0-group cod varies considerably from year to year (Anon., 1991a). Consequently, in years with a high proportion of small individuals, the index of abundance may be under-estimated compared with years with high larval growth rates or when spawning occurred earlier. At 30 m depth it is evident that the efficiency of the ET is far superior to that of the ST, and this also suggests that 0-group cod are, to a great extent, filtered by the large meshes of the ST. The small difference between ST length distributions at the surface and at 30 m could be because the depth dependency of length is greatest in the upper 25 m. During the postlarvae survey, the efficiency of the ST will be very low owing to the smaller size of the fish, and hence errors caused by any kind of variation in depth distribution may affect the survey results significantly.

There is no tendency for a lower mean catch in the wake of the propeller. Thus, bias owing to propeller wake avoidance, as suggested by Ona (1989), did not appear to be significant. However, the lower frequency of the largest individuals in the ET surface catches may indicate that these individuals do have an avoidance reaction very close to the surface. However, this could also be caused by length-dependent distribution, i.e. cod greater than 65 mm long are found in small amounts within the reach of the low-opening ET.

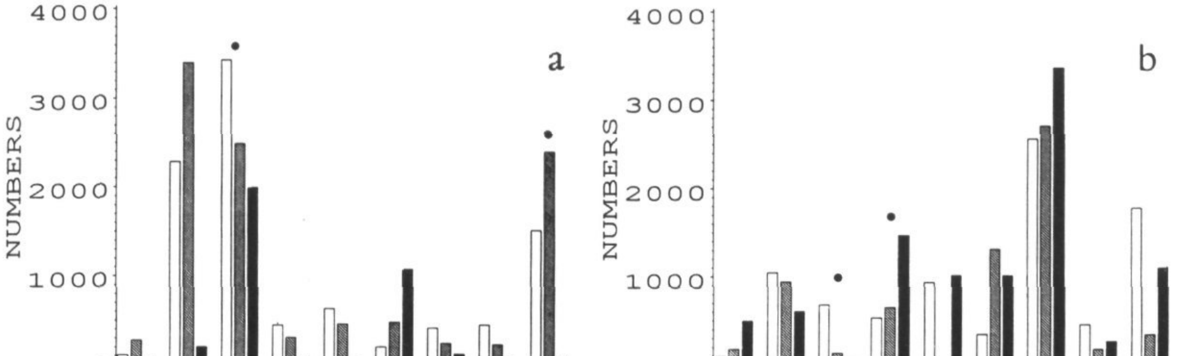

Figure 7. Catch rates of cod taken by the starboard (open columns), centre (hatched columns), and port (black columns) bags of the experimental trawl at surface (a) and at 30 m (b). Night hauls (18.30–23.20 GMT) are marked with black dots.

Variability in the bag catches of the individual surface hauls was particularly interesting and indicates a very patchy distribution of 0-group cod. The few available ST catches are less variable. This could be because patchiness is highest closest to the surface layer, and this region was not properly sampled by the ST owing to selectivity. Also, the sampling volume of an ST may have been large enough to reduce variability caused by a patchy distribution.

The less-than-optimal design of the current experiment, arising from the time difference between the ST and ET trawl stations and the low number of ST hauls, causes some uncertainty in analysis. In particular, the comparison of efficiency could be confounded by temporal and spatial variations. Some of the results, however, are clear and interesting, and can be summarized as follows:

- The new experimental trawl proved to be easily operated, and showed stable geometry and performance at 5 m and 30 m depths.
- The high catches and wide ranges of fish length obtained in the catches of the experimental trawl indicate a substantial step forward compared with the standard trawl currently in use.
- The standard trawl is very inefficient at catching small cod and is likely to provide misleading annual indices of abundance.
- The results make a good basis for new experiments to obtain better intercalibration between the two trawls and to improve the design of the new trawl.

Acknowledgements

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Assessing the reliability of fish density estimates by monitoring the swimming behaviour of fish schools during acoustic surveys

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Misund, O. A., Aglen, A., Johanessen, S. Ø., Skagen, D., and Totland, B. 1993. Assessing the reliability of fish density estimates by monitoring the swimming behaviour of fish schools during acoustic surveys. – ICES mar. Sci. Symp., 196: 202–206.

The swimming behaviour of schooling North Sea herring and Barents Sea capelin was recorded with a Simrad SR 240 sonar during acoustic surveys by RV "Johan Hjort". Horizontal swimming speed increased with fish length and declined with better sound propagation conditions. Herring schools exhibited avoidance when in front of the approaching vessel, behaviour which caused an underestimation of fish density in the order of 20%; capelin schools did not avoid the vessel.

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Introduction

In the vicinity of an approaching survey vessel, the swimming behaviour of fish is likely to reflect avoidance of the imposed noise stimuli (Olsen *et al.*, 1983). Such avoidance behaviour may change the distribution of fish in the path of a survey vessel, and induce a bias in acoustic estimates of fish abundance. According to a vessel avoidance model (Olsen *et al.*, 1983), the fish will swim radially out of the path of an approaching vessel. However, shadowing by the hull creates a directional noise field around the vessel, with a minimum in front and lobes of maximum intensity radiating to the sides (Urick, 1967). If fish aggregate in the path of the vessel as a response to the intensity distribution of the noise field, an upward bias in the recorded fish abundance may occur. Misund and Aglen (1992) have observed that herring schools tend to swim in the same direction and in a sideways-forward-sideways pattern in front of an approaching survey vessel. However, the noise level substantially increases very close to the vessel, and fast avoidance reactions may be elicited. The fish density recorded by the echo integration system underneath survey vessels may therefore be drastically reduced.

To investigate these avoidance hypotheses, it is necessary to record swimming behaviour of fish at long to very close range, when approached by a survey vessel. For pelagic schooling fish, this can be done with a hull-mounted, true motion sonar (Bodholdt and Olsen, 1977). We have applied a recently developed sonar unit, especially constructed for long-range detection of schools, which can be operated without a blind zone at short range. We have recorded herring schools in the North Sea and capelin schools in the Barents Sea during conventional acoustic surveys, and have analysed how the observed behaviour might affect estimates of fish abundance.

Materials

Recordings of schools were conducted by RV "Johan Hjort" during acoustic abundance estimation of herring in the North Sea in July 1991 and of capelin in the Barents Sea in January 1992. The schools were observed by sonar, both when the vessel was cruising (110 and 32 schools of herring and capelin, respectively) along predetermined transects at a speed of about 5.7 m s^{-1} (11 knots), and during pelagic trawling (41 and 14 schools of herring and capelin, respectively) when the vessel was manoeuvred at a speed of about 1.5–2.3 m s^{-1} (3–4.5 knots).

RV "Johan Hjort" is equipped with the Simrad SR 240 sonar. A spherical transducer enables this 24 kHz sonar to operate horizontally in an arc of up to 360°, and at the same time carry out vertical searches of 90 or 180° at any angle to the ship's course line (Fig. 1). This combination gives an optimal visualization of the horizontal and

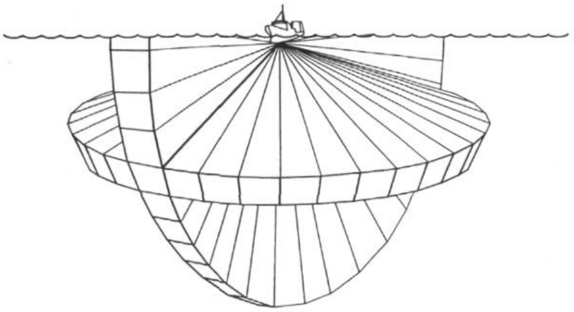

Figure 1. Horizontal/vertical transceiving combination of the Simrad SR 240 multibeam sonar; the width (−3 dB points) of single beams is 12° horizontally and vertically.

vertical distribution of a school of fish. Automatic target tracking and information about the school's speed and direction will make up the school's pattern of movement.

A feature of the SR 240 is its capability to operate in FM mode. Then the sonar transmits a combination code of two to eight different frequencies. When an echo returns, the sonar checks that the echo has the right code before displaying the signal. The result is a dramatic rejection of all unwanted noise signals and interference, and hence a great improvement in long-range detection of weak targets.

Methods

An HP 9000/720 workstation was connected to an RS 232 serial port on the sonar for ping-by-ping logging of telegrams that contain data on school position, behaviour, and vessel manoeuvring. A program written in the C-language and installed on the workstation initialized a data-logging session, read the sonar telegrams, and organized the data in standard files. The program also gave the opportunity to categorize a school recording by mode of vessel operation, species, school size, and sound propagation conditions.

When a school was detected by the sonar, a cursor was placed at the centre of the school projection and the target-tracking mode of the sonar was initialized. The sonar then tracked the school automatically, and calculated bearing and range vessel-to-school, horizontal swimming speed (V_h), depth, and heading of the school. Together with data on vessel speed from the ship's log and vessel heading from the gyrocompass, the sonar data were logged by the workstation ping by ping. Radial swimming direction (the swimming direction relative to direction of bearing vessel-to-school), radial horizontal swimming speed (the speed component, V_r, along the direction of bearing vessel-to-school), and vertical swimming speed (V_v) were calculated according to Misund (1990). To take account of the assumed directivity in the vessel noise, the measurements were divided into four sectors as: direction of bearing $< 15°$; $15° <$direction of bearing $< 45°$; $45° <$ direction of bearing $< 90°$; direction of bearing $> 90°$. Recordings within 50 m of the vessel were deleted from the analysis as the sonar tended to trace the outer edges of the schools when closer to the vessel.

Each school recording was categorized by the mode of vessel operation (cruising or pelagic trawling) and species. The size of the recordings was classified briefly as: *small* (1) – school area < 500 m^2; *medium* (2) – 500 m^2 $<$ school area < 1000 m^2; *large* (3) – 1000 m^2 $<$ school area < 5000 m^2; *very large* (4) – school area > 5000 m^2. In accordance with Misund and Aglen (1992), the recordings were further categorized to the prevailing sonar conditions (sound propagation conditions) as: *very bad* – school detection range < 400 m; *bad* – 400 m $<$ school detection range < 700 m; *good* – 700 m $<$ school detection range < 1000 m; *very good* – school dection range > 1000 m.

The recorded schools were regularly sampled by pelagic trawl to identify species and measure biological parameters. For herring and capelin, length to the nearest 0.5 cm, sex, and stage of maturation were noted for about 100 specimens from each sample.

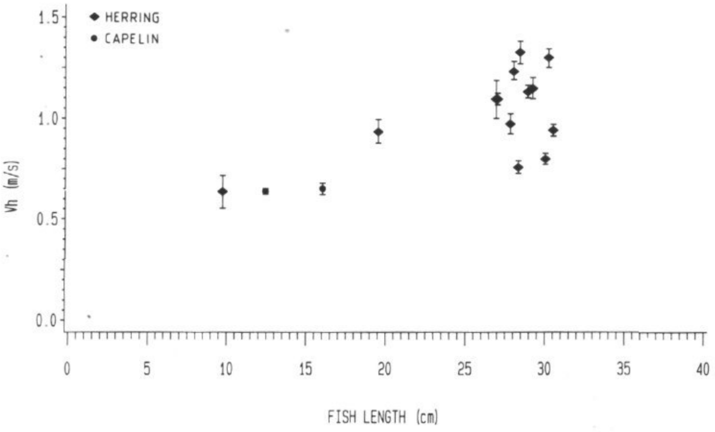

Figure 2. Relationship between average swimming speed (±s.e.) and fish length for capelin and herring schools.

Table 1. Nested linear models (SAS 1988) with distance, swimming depth, and time of day as continuous effects, using horizontal speed, radial speed, or vertical speed as dependent variable.

		Horizontal speed			Radial speed			Vertical speed		
	d.f.	F–value	p	r^2	F–value	p	r^2	F–value	p	r^2
Model	173	41.10	<0.001	0.23	30.49	<0.001	0.18	1.89	<0.001	0.01
Source										
Species	1	4.21	0.040		67.15	<0.001		6.72	0.010	
Sector (species)	6	2.74	0.012		41.81	<0.001		1.58	0.148	
Fish length (species sector)	49	16.19	<0.001		21.98	<0.001		1.67	0.002	
Operation mode (species sector length)	41	28.98	<0.001		21.54	<0.001		1.21	0.165	
School size (species sector length mode)	57	11.48	<0.001		13.22	<0.001		1.45	0.015	
Sonar conditions (species sector length mode)	16	27.99	<0.001		36.72	<0.001		1.72	0.036	
Distance	1	41.61	<0.001		0.02	0.877		0.02	0.887	
Depth	1	28.97	<0.001		36.58	<0.001		59.40	<0.001	
Time	1	4.44	0.035		67.02	<0.001		6.76	0.009	

Results

There were substantial variations in the swimming speed measurements of the schools. Linear models constructed by a reasonable nesting of the categories of the school recordings, and with swimming depth, distance vessel-to-school and time of day as continuous effects, explained about 20% of the variation in the measurements of horizontal and radial swimming speed (Table 1). A similar model for vertical swimming speed explained only 1% of the recorded variation.

Average horizontal swimming speed increased with fish length (Fig. 2, Table 1), but there was considerable variation among approximately similar length categories of herring schools. Radial speed was also significantly influenced by fish length (Table 1). Direction of bearing vessel-to-school significantly influenced radial speed (Table 1), but a systematic effect was detected only for herring (Table 2). This species clearly exhibits avoidance when less than 45° in front of the approaching vessel (average radial speed significantly $> 0\ \mathrm{m\ s^{-1}}$), but ceases avoidance when behind 45° relative to the vessel

Table 2. Average and standard deviation of observed swimming speeds ($\mathrm{m\ s^{-1}}$) of schools related to sector relative to the vessel, mode of vessel operation, school size and sonar conditions. V_H: horizontal speed; V_R: radical speed; V_V: vertical speed; s.d.: standard deviation; N: number of observations; B: direction of bearing vessel-to-school; CR: cruising; TR: trawling; S: small; M: medium; L: large; VL: very large; B: bad; G: good; VG: very good; p: level of significance, Kruskal-Wallis test.

	Sector					Mode		
	B<15°	15°<–B<45°	45°<B–<90°	B>90°	p	CR	TR	p
Capelin								
V_H	0.61	0.57	0.74	0.62	<0.05	0.75	0.55	<0.05
s.d.(V_H)	0.45	0.43	0.54	0.46		0.51	0.42	
V_R	0.03*	−0.01*	−0.08	0.01*	<0.05	−0.06	0.03	<0.05
s.d.(V_R)	0.48	0.51	0.60	0.53		0.59	0.48	
V_V	−0.08*	−0.02*	0.03*	0.03*	<0.05	0.02*	−0.06	<0.05
s.d.(V_V)	0.72	0.78	0.94	0.90		1.02	0.75	
N	440	1098	1411	2976		2801	2874	
Herring								
V_H	1.01	0.95	1.05	1.05	<0.05	1.16	0.91	<0.05
s.d.(V_H)	0.71	0.77	0.86	0.78		0.84	0.71	
V_R	0.26	0.21	0.00*	−0.31	<0.05	−0.13	−0.05	<0.05
s.d.(V_R)	0.99	0.90	0.96	0.90		1.05	0.84	
V_V	0.03*	0.06*	0.02*	−0.03*	<0.05	−0.05*	0.03	<0.05
s.d.(V_V)	1.62	1.48	1.51	2.78		2.97	1.28	
N	1810	3426	3862	9429		8935	9592	

*Not significantly different from zero.

(average radial speed not different from or significantly < 0 m s^{-1}). Both capelin and herring were swimming 0.2–0.25 m s^{-1} faster when the vessel was cruising than when pelagic trawling (Table 2). Even if there was a significant influence of mode of vessel operation on radial speed also (Table 1), average radial speed was close to 0 m s^{-1} for both species irrespective of whether the vessel was cruising or towing the trawl.

Average horizontal speed increased for capelin schools of larger size (Table 1), but this effect was not present for herring schools. Radial speed was also significantly influenced by school size (Table 1), but no systematic increase or decrease with school size was detected either for capelin or for herring (Table 2). For both species, average horizontal swimming speed declined the better the sonar conditions (Table 1). Radial speed was also significantly influenced by sonar conditions (Table 1), and herring clearly avoided the vessel when sonar conditions were very good (average radial speed = 0.25 m s^{-1}, Table 2). There was a weak increase in horizontal speed the deeper the swimming of the schools, both for capelin ($r = 0.26$, $p < 0.001$) and for herring ($r = 0.13$, $p < 0.001$).

All capelin schools observed by the sonar in front of the vessel were recorded at the echo sounder. That the capelin were not avoiding the vessel is also evident from rather straight average traces of the recorded schools (Fig. 3a). For herring, the avoidance in a 45° sector to each side in front of the vessel is reflected in a tendency to swim towards the path of the vessel. This is clearly seen in the average traces within 200 m to each side (Fig. 3b). However, 44% of the herring schools recorded within 50 m to either side of the path of the approaching

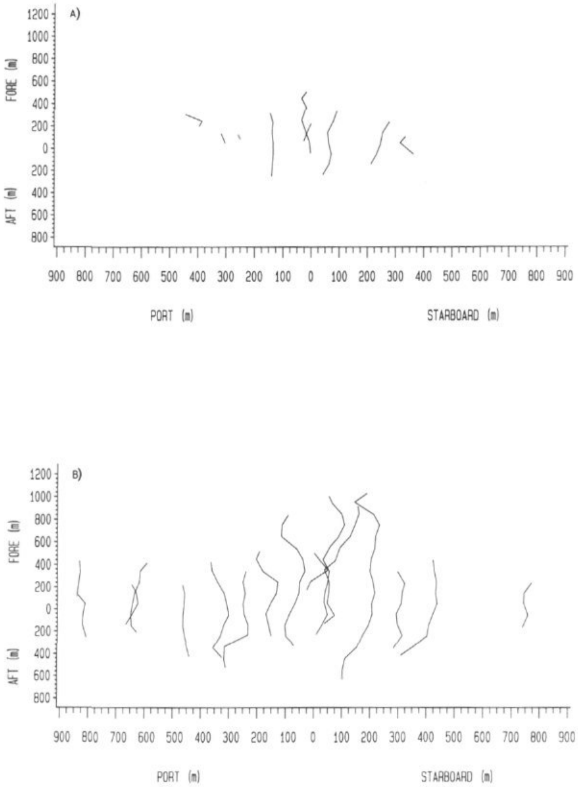

Figure 3. Average swimming traces of schools related to the cruising vessel. The schools are grouped according to the initial coordinates fore and to the side in intervals of 100 m. For each group, an average swimming trace is calculated from fore to aft. (A) Capelin schools, Barents Sea, January 1992. (B) Herring schools, North Sea, July 1991.

Table 2 Continued.

	School size					Sonar conditions			
	S	M	L	VL	p	B	G	VG	p
Capelin									
V_H	0.51	0.66	0.80	1.21	<0.05	0.78	0.68	0.59	<0.05
s.d.(V_H)	0.42	0.48	0.43	0.59		0.55	0.49	0.45	
V_R	−10.03	0.04	−0.27	−0.05*	<0.05	0.06*	0.02	−0.05	<0.05
s.d.(V_R)	0.42	0.56	0.57	0.82		0.66	0.57	0.51	
V_V	0.00*	−0.02*	0.04*	−0.17*	<0.05	−0.06*	−0.05*	0.00*	<0.05
s.d.(V_V)	0.45	1.00	0.91	1.13		1.38	0.91	0.79	
N	1670	3841	264	150		305	2360	3260	
Herring									
V_H	0.95	1.16	1.10	1.01	<0.05	1.11	0.94	0.82	<0.05
s.d.(V_H)	0.75	0.81	0.84	0.75		0.78	0.78	0.68	
V_R	−0.07	−0.10	−0.14	−0.11*	<0.05	−0.14	−0.05	0.25	<0.05
s.d.(V_R)	0.88	1.03	1.03	0.94		1.03	0.84	0.57	
V_V	−0.05*	0.08*	0.02*	0.03*	>0.05	−0.04*	0.05	−0.07*	<0.05
s.d.(V_V)	2.57	2.07	1.45	0.71		2.79	1.33	0.68	
N	10181	4733	3104	509		10255	7881	392	

*Not significantly different from zero.

vessel, when within an interval from 50 m to 200 m in front, were not recorded at the echo sounder. This indicates sideways avoidance just in front of the cruising vessel, a tendency that decreased during trawling as 72% of the schools aimed at were recorded by the echo sounder. Generally, the schools within the path of the vessel that avoided recording by the echo sounder were smaller (average size category = 1.7 and 1.1 for recorded and unrecorded schools, respectively, $p < 0.05$) and swimming shallower than those that were recorded (average swimming depth = 41.9 m and 19.7 m for recorded and unrecorded schools, respectively, $p < 0.05$).

Discussion

Ping-to-ping recordings of schools by sonar have given plausible estimates of swimming speed for both capelin and herring. The average speed recorded for these species are within the range of measurements of their endurance speed (Miller and McInerney, 1978; He and Wardle, 1988). However, there was a substantial variation in the recordings of swimming speed; linear models constructed by nesting the categories explained only about 20% of the variation in horizontal and radial speed and only 1% for vertical speed. Some of the variation may be caused by the method of target tracking of the sonar, which is based on ping-to-ping calculation of the echo gravity centre of the school recording. Random variations in the acoustic back-scattering strength from different parts of the school may thereby induce substantial variation in sonar measurements of swimming speed. Nevertheless, there were similar variations in the measurements of Misund and Aglen (1992) which quantified the movements of the school centre at 10 s intervals. This similarity indicates that a substantial amount of the recorded variation is real, and probably reflects internal dynamics of moving schools. As a sonar with 12° vertical beam width gives an uncertain estimate of the depth of a target when observed at low tilt angle, the large variation in vertical speed is probably due to measurement errors.

As expected, average swimming speed increased with fish size, but there was substantial variation among groups of nearly the same length of herring. This could be caused by differences accounted for by the various categories of the sonar recordings. Both species swam more slowly during pelagic trawling than when recorded during cruising. RV "Johan Hjort" is, however, 5–10 dB more noisy in the 100–1000 Hz range during trawling than when cruising. Despite this amplitude difference, the fish will experience a more rapid change in the sound pressure gradients when the vessel is cruising, to which they may react by an increased swimming speed. A similar effect probably explains the reduction in swimming speed in good propagation conditions, because the fish can then detect the noise at longer range and will sense a more gradual increase in sound pressure as the vessel approaches (Misund and Aglen, 1992).

The larger the schools of capelin, the faster the swimming speed. The largest schools were formed by mature fish exclusively, and were recorded during spawning migration. In this stage of the life history, the capelin may perform a faster endurance speed than in other situations. Also, it is the experience of fishermen that during spawning migration capelin do not react much to noise from vessels. In agreement with this, we recorded no avoidance by capelin schools of the approaching survey vessel.

When in a sector of less than 45° to each side in front of the vessel, herring showed clear avoidance behaviour, and about 35% of the schools in the path of the vessel in total were not recorded by the echo sounder. A similar frequency of missed schools was recorded during two preceding cruises in the North Sea (Misund and Aglen, 1992). The missed schools were, however, both smaller and swimming shallower than those recorded, and a substantial fraction of these schools may therefore have been missed, owing both to randomness and to distribution in the upper blind zone. However, the high frequency of missed schools indicates that the biomass was underestimated, but probably by less than 20% when account is taken of a smaller size and about 10% randomly missed schools (Misund and Aglen, 1992).

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Vertical size distribution of shrimps (*Pandalus borealis*) in the water column 0 to 8 m off the seabed

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The vertical distribution of shrimps was examined during different periods and at different locations in Spitsbergen (Isfjorden) and northern Norway (Lyngen). A shrimp-sampler, i.e. a steel frame 3 m wide and 8 m high, with an array of fine-meshed bags placed at different heights, was towed at a speed of 1.7 to 1.9 knots along the bottom during one-nautical-mile hauls. Sampling was made at fixed time intervals, covering 24 h periods. Samples from all 15 mesh bags were examined, and size distributions of shrimps in the different strata were calculated.

Comparison between the shrimp-sampler and a sampling trawl indicates poor efficiency of the trawl. Shrimps are lost above the headline and under the fishing line, thus providing inaccurate estimates of population size and demography.

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Introduction

The standard survey method for shrimps, the "swept area method", depends upon the availability of the populations and their catchability with that trawl gear. This may bias the estimation of age-group abundances by under-estimating the younger animals (Fréchette and Parsons, 1981).

Shrimps (*Pandalus borealis*, Krøyer) undergo diurnal vertical migration (see review by Shumway *et al.*, 1985) which is reflected in differences in catch rates by day and night. The largest catches are found during the day (Smidt, 1978) when shrimps are available in the catching zone of the gear. Vertical migratory behaviour is important in analyses of catch data for *P. borealis*, and will bias the estimates unless compensation is made for this behaviour. Variations in trawl geometry (wing spread and trawl height), which will mainly be depth dependent (Godø and Engås, 1990), are also likely to introduce sources of error in the estimates.

The vertical height of any bottom sampling device should approximate the off-bottom distribution of the target species (Beardsley, 1973), and knowledge of the near-bottom vertical distribution of shrimps is therefore considered essential to the design of an effective shrimp-sampling trawl. Experiments with fine-meshed bags placed under the fishing line of a sampling trawl showed that these bags caught 27 times more (litres/unit volume) than the codend of the trawl (Nilssen *et al.*, 1986).

To investigate the vertical distribution of *P. borealis* in the water column, rigid samplers collecting shrimps at different height intervals off the bottom have been used both in Canadian (Fréchette *et al.*, 1981) and in Icelandic waters (Einarsson, 1983).

Materials and methods

The experiments were carried out in Lyngen fjord, northern Norway (depth: 250–260 m), during 2 to 3 October 1990 and 20 to 21 March 1991 (sunrise between 06.00 and 18.00), and in Isfjorden, Spitsbergen (depth: 220–240 m) during 1 to 2 August 1990 (24 h sun). All the trials were carried out on board the 30.5 m RV "Johan Ruud" (1000 bhp).

The shrimp-sampler was originally constructed as a 3 m wide by 4 m high steel frame equipped with 40 m long double bridles and flat, oval otter boards (200 kg, 1.2 m^2). During the experiments in Lyngen in 1991, however, an extra section (1 m wide × 4 m high) was attached on top of this frame, thus increasing the sampling height to 8 m. The layout of the shrimp-sampler is

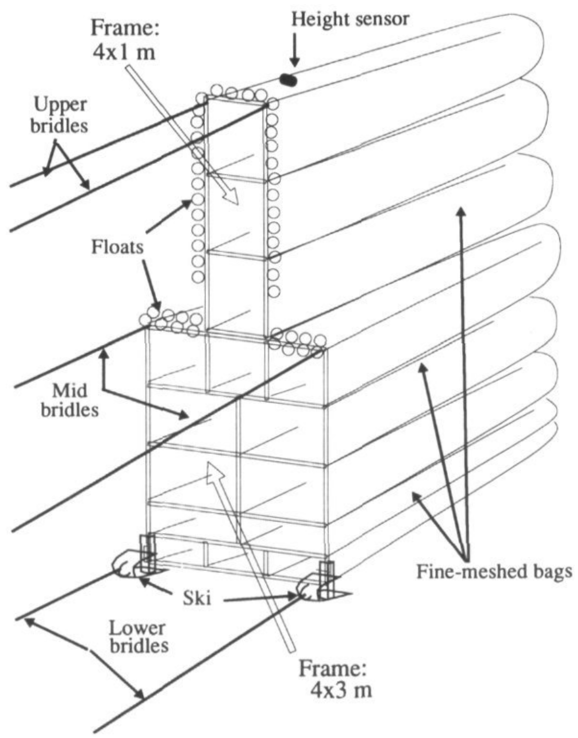

Figure 1. Construction and experimental layout of the rigid shrimp-sampler. The figure shows the full 8 m tall version used in Lyngen, northern Norway, in March 1991. Earlier experiments during 1990 in Lyngen and in Spitsbergen lacked the upper, 4 × 1 m frame.

shown in Figure 1. Separate bags with a mesh size of 18 mm (front) and 4 mm (codend) were lashed to the openings (15 in total). Plastic floats on the frame provided a slightly negative buoyancy.

The clearance between the sea bottom and the lower part of the shrimp-sampler was 30 cm during the experiments in Isfjorden and Lyngen, March 1991. An attempt to use a 10 cm bottom clearance was made during the experiments in Lyngen, October 1990, but owing to heavy mud deposits, the lower bags had to be opened during the tows (i.e. yielding a bottom clearance of 60 cm). A total of 28 valid hauls were conducted during the three different periods: 11 in Isfjorden and 17 in Lyngen (10 during October 1990 and 7 during March 1991).

Catch comparisons were made between the shrimp-sampler and a standard sampling trawl, i.e. a modified 1280 mesh × 44 mm two-panel shrimp trawl with a codend mesh size of 35 mm. The distance between the fishing line of the trawl and the seabed could reach a maximum height of 85 cm (i.e. half the bobbin diameter plus the length of the toggles of the fishing line). Towing at a speed of 1.9 knots (and depths of 220 to 260 m), the trawl gained a wingspread of 18 to 19 m and a vertical opening height (from the seabed to the headline) close to 6 m. The difference in sampling area between the shrimp-sampler and the sampling trawl is illustrated in Figure 2.

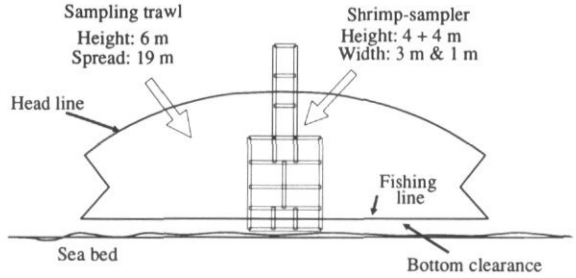

Figure 2. Sketch (front view) showing the difference in geometry and sampling area between the standard sampling trawl and the rigid shrimp-sampler.

Effective towing distance along the bottom for both the frame and the trawl was held constant at one nautical mile at a towing speed of 1.7 to 1.9 knots (GPS measurements). Scanmar sensors were used to monitor bottom contact and gear performance during the trials.

Results

Length distributions at different heights

The accumulated length-frequency distributions (LFDs) of *P. borealis* at each height interval during the three experiments are shown in Figure 3. The LFDs of shrimps, and thus the age-group strength, differed from one level to another above the bottom. Proportionally more small shrimps (males) were found close to the bottom, while larger shrimps (transitionals and females) were more abundant in the highest levels. Comparable patterns or trends of LFDs for *P. borealis* were found both in the Isfjorden and in the two Lyngen experiments.

Distribution and abundance fluctuations of shrimps

On average, more than 50% of shrimps of all sizes were caught by the three lowest nets (0 to 2 m off the bottom) of the shrimp-sampler, indicating that shrimps were most abundant close to the bottom in the supra-benthic layer sampled. During the experiments, the smallest shrimps were more abundant in the levels close to the bottom, while the density of older individuals was more balanced among the different height intervals.

Abundance of all size groups fluctuated diurnally between the different tows, and the densities changed by several orders of magnitude, especially for the smallest (youngest) shrimps. The daylight catches were higher (by weight) than night catches, during the experiments in Lyngen, October 1990, indicating a near-bottom distribution during daylight hours. This pattern was,

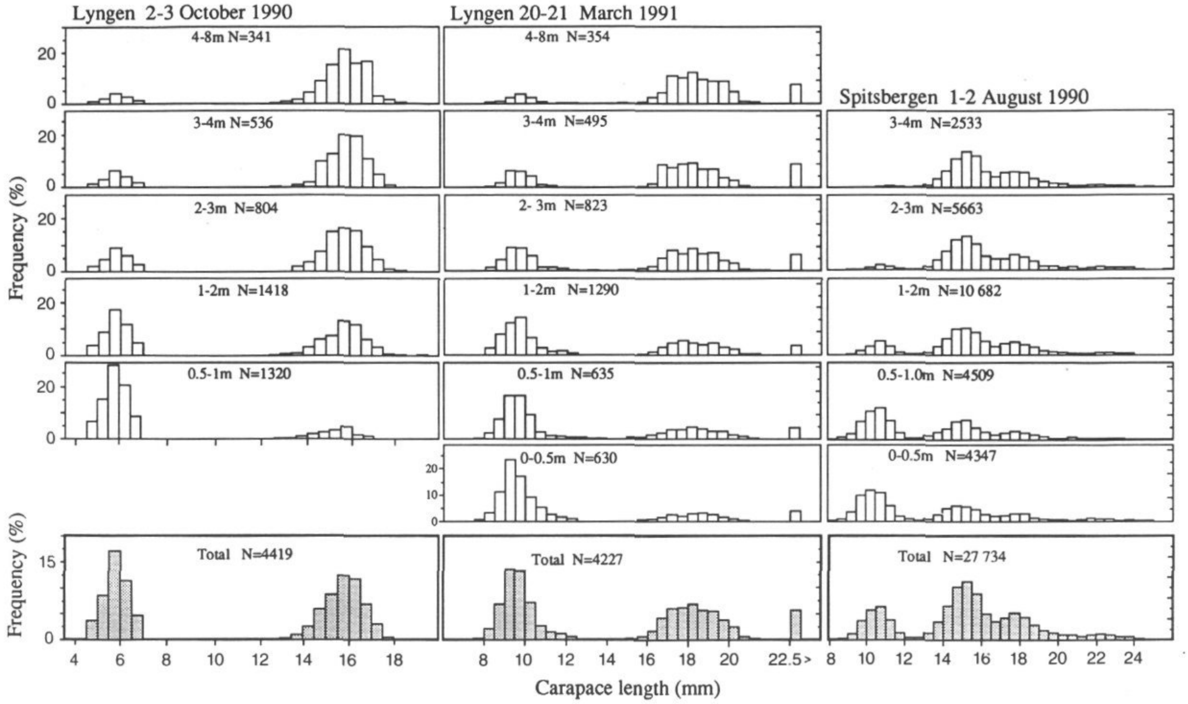

Figure 3. *Pandalus borealis.* Relation of length-frequency distribution to distance off bottom for the shrimp-sampler tows; 10 tows in Lyngen 2–3 October 1990, 7 tows in Lyngen 20–21 March 1991, and 11 tows in Isfjorden 1–2 August 1990.

however, less evident during the experiments in Isfjorden (Spitsbergen) and in Lyngen, March 1991. A shift towards gradually lower densities of young shrimps after midday occurred in the Isfjorden experiments, while the opposite effect was observed during both periods in Lyngen.

Comparison of LFDs between the shrimp-sampler and the trawl

A comparison was made between four tows with the shrimp-sampler and four tows with the standard sampling trawl (using a 35 mm codend) during the March 1991 experiments in Lyngen. In this experiment, the highest frequencies of shrimps caught by the shrimp-sampler were in the range of 8 to 12 mm carapace length. Only a few shrimps in this size range were caught by the trawl, demonstrating a very low (trawl) catch efficiency on the smallest shrimps (Fig. 4).

Discussion

The smallest shrimps are concentrated close to the bottom, while larger shrimps are more evenly distributed in the water column within the examined strata. Despite large differences in locations, light and abundance of shrimps, this typical behavioural pattern was observed in all experiments.

The catches of shrimps (per unit volume swept) varied between day and night hauls, with the biggest catches early in the morning and during the day. This effect seems to be very common in the fishery for *P. borealis* (see review by Shumway *et al.*, 1985). The highest densities of shrimps were found in the first 2 m off the seabed, and the youngest (smallest) shrimps escaping under the fishing line of the trawl may be underestimated. These findings are in agreement with

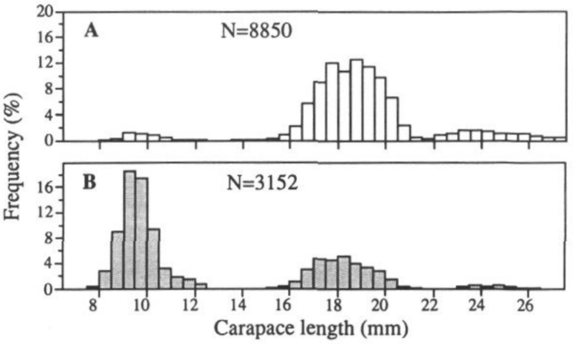

Figure 4. *Pandalus borealis.* Accumulated length-frequency distributions for four tows with the standard shrimp-sampling trawl (A) and four tows with the shrimp-sampler (B) carried out at comparable hours in Lyngen 20 to 21 March 1991.

reported results on escape studies in low-opening trawls with relatively large bottom clearance (Nilssen *et al.*, 1986).

It should be stressed that the comparison between the shrimp-sampler and the standard sampling trawl was based on only eight hauls during the March 1991 experiments, and that the shrimp catches were small. The results showed, however, poor trawl efficiency on the smallest shrimps. This could reflect codend size selection or escape between the fishing line and the seabed. Valdemarsen and Isaksen (1989) found no significant differences in size selection for *P. borealis* when changing the mesh size in the codend. Photographic observations of *P. borealis* showed that nearly all shrimps are in near contact with the bottom (Kanneworff, 1978). Andreasson and Bardarsson (1992) found larger quantities of smaller shrimps in the catches when changing from a bobbin ground gear to a rockhopper ground gear (i.e. to a smaller distance between fishing line and the bottom). These observations and experiments indicate that the escape of small shrimps below the fishing line of the trawl is more important than codend size selection. We think, however, that any sampling device used for small animals like *P. borealis* should be equipped as standard with fine-meshed inner nets to avoid biased data due to possible codend size selection.

The estimates of population sizes and demography obtained by sampling trawls will depend on several factors; the gear, near-bottom escape and underestimation of the smallest shrimps are among the most important. Godø and Engås (1990) found large depth variations in swept area and sampling height due to the flexible nature of the trawl. Furthermore, the vertical migration and distribution of shrimps may vary in time and space. Shrimps are caught and observed up to 150 m off the bottom during daytime, and from the bottom to the surface at night (Klimenkov *et al.*, 1978, Parsons *et al.*, 1991).

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Management implications of changes in by-catch rates of Pacific halibut and crab species caused by diel behaviour of groundfish in the Bering Sea

Sara A. Adlerstein and Robert J. Trumble

Adlerstein, S. A., and Trumble, R. J. 1993. Management implications of changes in by-catch rates of Pacific halibut and crab species caused by diel behaviour of groundfish in the Bering Sea. – ICES mar. Sci. Symp., 196: 211–215.

This study compares day and night by-catch rates of prohibited species (ratio of prohibited species to groundfish catch) in US domestic bottom-trawl fisheries for Pacific cod (*Gadus macrocephalus*) and walleye pollock (*Theragra chalcogramma*) in the Bering Sea to identify management options to reduce by-catch. Bottom trawl fisheries in the Bering Sea cause significant by-catch mortality of Pacific halibut (*Hippoglossus stenolepis*) and other prohibited species such as king crab (*Paralithodes camtschatica*) and Tanner crabs (*Chionoecetes* spp.) By-catch rates are higher during night hours than during the day. We propose that by-catch differences are caused by diel vertical migration and other behavioural characteristics of the species that result in fluctuations of their relative abundance near the seabed between the two time periods. Avoiding night bottom fishing in the Pacific cod and walleye pollock fisheries may permit by-catch rate reduction. Fishing exclusively during day hours could produce total savings from 13 to 16% of the observed by-catch of halibut, king crab, and Tanner crabs.

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Introduction

By-catch of prohibited species such as Pacific halibut (*Hippoglossus stenolepis*), king crab (*Paralithodes camtschatica*), and Tanner crabs (*Chionoecetes* spp.) in the Bering Sea causes tremendous losses, both in groundfish and in prohibited species fisheries. Management regulations for by-catch in the region set quotas for prohibited species (tonnes of halibut and number of crabs) in the various groundfish fisheries and require prompt discard of the by-catch to the ocean. By-catch quotas are often reached before the groundfish quotas are taken, and these fisheries are closed before their allowances are harvested. Among the bottom trawl fisheries in the region, catches with high proportion of Pacific cod (*Gadus macrocephalus*) experience high halibut by-catch rates. Fishermen have reported that higher by-catch rates occur during night hours than during the day. Variation in these rates is most probably related to the diel vertical migration of Pacific cod. Cod species, usually found in close association with the seabed during day hours, have been reported to migrate to the surface during the night (Beamish, 1966; Turuk, 1973). The goal of this study is to investigate the reported day and night differences in by-catch rates and to understand the behavioural processes of the various species involved in the fishery to use this information for management purposes. Our approach was statistically to compare fishery data, and to complement the results with biological information on the species' behaviour.

Material and methods

Pacific halibut and crab species by-catch rates vary with the composition of the groundfish species in the catch (i.e. walleye pollock (*Theragra chalcogramma*), Pacific cod, yellowfin sole (*Limanda aspera*), rock sole (*Lepidopsetta bilineata*) and other flatfish) (Berger *et al.*, 1989; Clark, 1990; Adlerstein, 1991). This analysis investigates whether by-catch rates in the Pacific cod and walleye pollock fisheries vary from day to night after accounting for systematic changes in species composition in the catch. The study uses data from individual bottom trawl hauls from the 1990 domestic operations in the western region of Area 511 in the Eastern Bering Sea (Fig. 1). Pacific cod is part of several bottom-trawl multispecies fisheries and is an important component of the total catch of Pacific cod and walleye pollock fisheries. Fishing operated in the area from January to May. Pacific cod is also caught by trawls in Areas 513, 517, 519, 521, and 522, but we selected Area 511 because of data availability. Data were provided by the National Marine Fisheries Service (NMFS), Seattle, and are from a haul by haul database collected by observers in the North Pacific and Bering Sea (NORPAC) generated by a mandatory observer programme. Records contain the weight, numbers, and length frequencies of Pacific halibut, number of crabs, total catch weight, and weight by groundfish species. Records also contain information about trawl operations such as gear type, date, location, and time of set and retrieval of the nets. Day hauls are those set and retrieved between sunrise and sunset, and night hauls are those taken after evening twilight and before morning twilight. Hauls extending from day to night periods were classified as transitional.

Comparison of day and night rates used an analysis of covariance (ANCOVA) (Zar, 1984), where by-catch rates are a function of the catch composition. The analysis used the Generalized Linear Interactive Modelling (GLIM) System (Royal Statistical Society 1987). The proportions of Pacific cod and rock sole in the catch were incorporated as covariates, and month (January to May) and time period of the day were included as fixed factors. Walleye pollock, an important component of the catch, was not included as a covariate because Pacific cod and pollock are collinearly related in these fisheries (Adlerstein, 1991). Yellowfin sole, another important component of the overall catch, was not included as covariate because it was not part of the domestic fisheries in 1990. Month was used as a fixed factor because by-catch of halibut and crab species experiences temporal variations (Adlerstein, 1991).

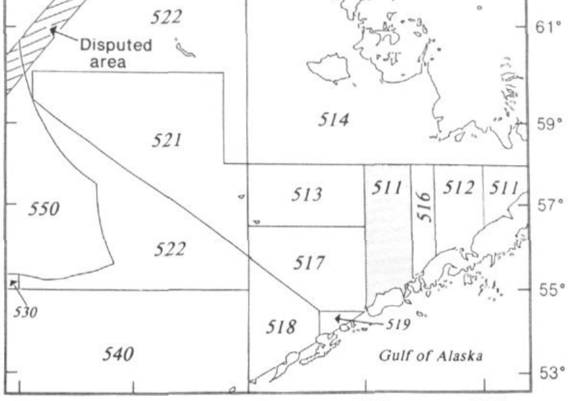

Figure 1. Regulatory areas in the Bering Sea/Aleutian Islands. Data for the analysis were taken from the stippled area of Area 511.

Data were subjected to the model $Y_{ij} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + b1_{ij}X1 + b2_{ij}X2$ where Y is the natural logarithm of the prohibited species by-catch rate + 1 (in kilograms of halibut or number of crabs per tonne of groundfish) for the ith month and the jth time periods, X1 and X2 are the proportions of Pacific cod and rock sole in the catch, and α and β are model intercept parameters for the month and time period modifying the overall mean μ. The logarithmic transformation of the by-catch data normalized the distribution of the errors. We fitted the full model and tested for differences in the model slopes between month and time of the day periods as well as for differences between the means. Applying day parameters of the model together with night catch proportions and comparing the results with estimates obtained from night parameters, we were able to estimate monthly savings of prohibited species by-catch that would be obtained if the night catches of fisheries under consideration were harvested during day hours.

Results

Comparison of the parameter estimates of the three time categories (β_i) in fitting the full by-catch model revealed that by-catch rates of halibut and the crab species in the transition category were not significantly different from the night rates (halibut: $p(|t| \geq 0.816) > 0.2$; king crab: $p(|t| \geq 1.108) > 0.2$; Tanner crab: $p(|t| \geq 0.891) > 0.2$). Thus, for further analysis we combined the transition and night categories. Observed mean by-catch of the combined data for the three prohibited species was higher during night hours (Fig. 2). Results of the ANCOVA using day and night-time categories showed that three-way interactions between Pacific cod, month and day/night periods were not significant at an α level of 0.05 ($F_{4,1370} = 2.152$; $p = 0.072$), nor between rock sole, month and day/night periods ($F_{4,1370} = 1.961$; $p = 0.098$). Two-way interaction between Pacific cod and month was not significant ($F_{4,1378} = 1.846$; $p = 0.118$), nor were the interactions between rock sole and month ($F_{4,1378} = 1.653$; $p = 0.159$), Pacific cod and day/night period ($F_{1,1378} = 2.729$; $p = 0.099$), and rock sole and day/night period ($F_{1,1378} = 2.575$; $p = 0.109$). These results allowed us to perform an ANCOVA (intercepts) using common slopes (b1 and b2) models. Results from the ANCOVA indicated that by-catch rates vary by time of the day ($p = 0.004$), by month ($p < 0.0005$), and with the proportion in the catch of Pacific cod ($p < 0.0005$) and rock sole ($p < 0.0005$). The interaction between month and time of the day was not significant ($p > 0.25$)

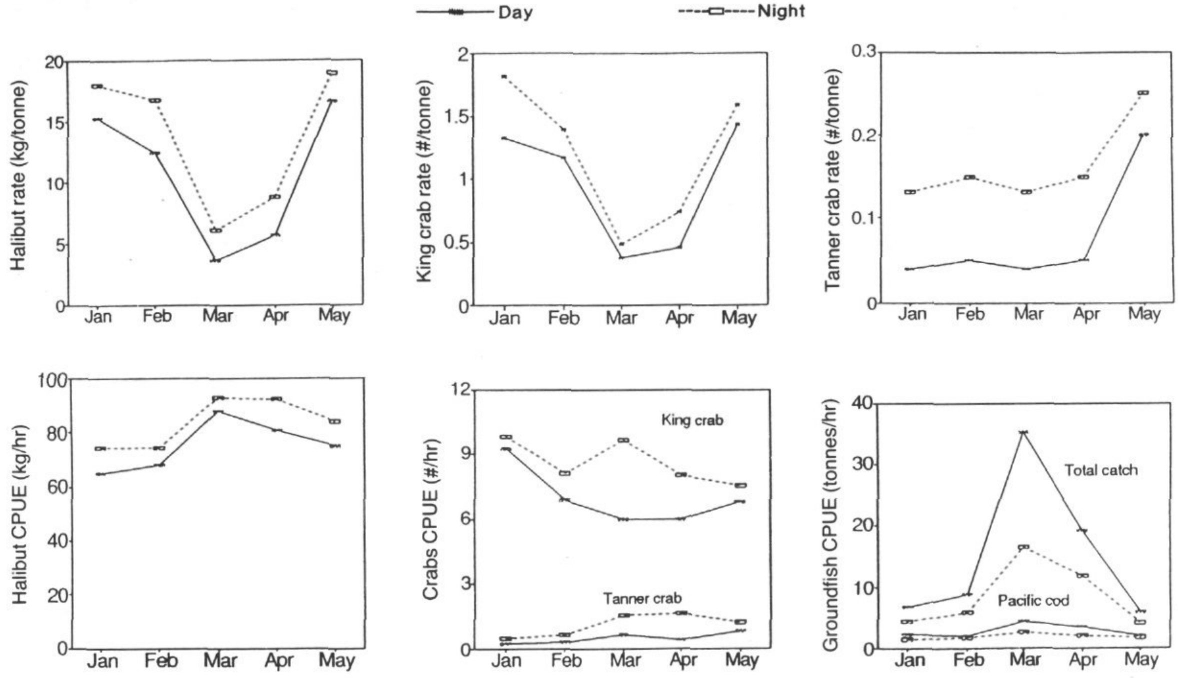

Figure 2. Observed mean by-catch rates of the prohibited species, and catch per hour of groundfish and prohibited species in Area 511, 1990.

(Table 1). A Filliben test (Filliben, 1975) performed on the ordered model residuals indicated no evidence against assuming normal distribution of the errors (Filliben coefficient $= 0.9989$, $p < 0.05$).

Inspection of the parameter estimates of the common slopes model incorporating month, time of the day, and proportions of cod and rock sole, shows that the intercept of the model is increased during night hours over the day intercept (Table 1). Thus, since the slopes remain the same during the two time periods, halibut by-catch rates for a given catch species composition are higher at night than during the day. We estimated potential savings obtained by fishing during day hours by using parameters in Table 1 and catch composition. The results indicated that if night catches were taken during the day, the by-catch rates would be reduced by 16.2% in January, 16.4% in February, 17.4% in March, 35.4% in April, and 15.2% in May.

Results of the ANCOVA on the by-catch data of the two crab species showed similar results to those obtained from the halibut data. Three- and two-way interactions between the covariates and factors were non-significant ($p > 0.1$ in all cases). This allowed us to perform the ANCOVA using common slopes models. Results from the ANCOVA on the king crab data using the common slopes model revealed that day and night by-catch rates are significantly different from each other ($p < 0.0005$)

Table 1. Results of analysis of covariance of the by-catch rate (Y) of Pacific halibut for the effect of month (January to April), and time of the day (night and day) accounting for the proportion of Pacific cod (X1) and rock sole (X2). Covariates, factors, and interactions are assessed simultaneously, with each effect adjusted for all other effects in the model.

Source of variation	SS	DF	F	P
Month	178.80	4	43.525	<0.0005
Day/night	8.44	1	8.173	<0.004
Rock sole	61.37	1	61.367	<0.0005
Cod	87.02	1	87.016	<0.0005
Month, day/night	2.613	4	0.635	>0.25
Residual	1426.8	1389		

Parameter estimates for the model including significant variables $Y_{ij} = \mu + \alpha_i + \beta_j + b1X1 + b2X2$

	Estimate	s.e.	Parameter
1	1.680	0.1003	μ (January, day)
2	−0.2956	0.1017	$\alpha 2$ (February, day)
3	−0.6809	0.1124	$\alpha 3$ (March, day)
4	−0.3854	0.0983	$\alpha 4$ (April, day)
5	0.3978	0.0911	$\alpha 5$ (May, day)
6	0.1659	0.0578	$\beta 2$ (night)
7	2.047	0.2555	Rock sole (covariate) (b1)
8	1.189	0.1232	Pacific cod (covariate) (b2)

$\alpha 1$ and $\beta 1$ are constrained to 0. Standard errors of the intercept αi and βj are of the difference between the corresponding factor levels and μ.

and that the night intercept is increased over the day intercept. All other variables were significant in determining by-catch ($p < 0.0005$). We estimated rate reductions as before. Rates could be reduced by 17.2% in January, 20.8% in February, 28.7% in March, 26.4% in April, and 19.0% in May. Results from the ANCOVA using the reduced model on the Tanner crab data indicated that day and night by-catch rates are significantly different from each other ($p < 0.005$) and that the night intercept is increased over the day intercept. We estimated rate reductions to be 31.9% in January, 34.9% in February, 37.7% in March, 34.4% in April, and 39.4% in May.

By-catch rates are determined by the relative abundance of prohibited species and groundfish in the catch. Catch per unit effort (c.p.u.e. in tonnes/h) of groundfish decreases significantly at night: $p(|t| \geq 2.724) < 0.005$ for all month (Fig. 2). In particular c.p.u.e. of Pacific cod decreases during the night: $p(|t| \geq 1.953) < 0.05$ for all months. Lower c.p.u.e. of the groundfish catch during night suggests that fish are less available or vulnerable to the net near the seabed during those hours. Lower availability is consistent with hydroacoustic observations in the Bering Sea that the two main species in the catch, Pacific cod and walleye pollock, rise off the bottom during the night (E. P. Nunnallee, pers. comm., NMFS, Seattle). Also, catch rates of cod (*Gadus morhua* L.) in bottom trawl surveys have been reported to be higher by day (Engas and Soldal, 1992). Halibut, king crab and Tanner crab, c.p.u.e.s by month are consistently higher at night (Fig. 2), although the differences between the two time periods are not significant ($p(|t| \geq 0.543) > 0.5$; $p(|t| \geq 1.528) > 0.1$; $p(|t| \geq 1.679) > 0.1$). Higher c.p.u.e. can be due to increased vulnerability or availability of prohibited species near the seabed during night hours. We observed that length frequency distributions of halibut by-catch during day and night hours show significant differences (Kolmogorov-Smirnov two-samples test p of $Z < 0.0001$). The tendency is to find higher proportions of fish larger than 50 cm in night hauls than in day hauls. It is possible that fish vulnerability changes between dark and light periods because large halibut are more likely to avoid the nets during light periods. No information was accessible to us to investigate diel changes in availability. Nevertheless, Walsh (1991) reported no evidence of changes of availability of American plaice or yellowtail flounder in relation to light intensity. The variation of the crab species, c.p.u.e. between day and night periods may be due to differences noted in behaviour between a period of diurnal rest and one of nocturnal foraging, as noted by Dew (1989) in king crabs. Nocturnal aggregations result in pods, which are accumulations of several hundred to several thousand crabs. It is conceivable that nocturnal activity may increase availability compared with the day situation when crab are resting in a hiding site.

Discussion and conclusion

By-catch rates of prohibited species in the walleye pollock and Pacific cod bottom trawl fisheries in the Bering Sea were found to be higher during the day than during night hours. Increase in halibut and crab by-catch rates at night is probably the result of the behaviour of the species involved in the bottom trawl fisheries. The relative abundance of the groundfish (mainly walleye pollock and Pacific cod) on bottom decreases during the night, seemingly because species migrate towards the surface during the night. Observations of cod migrating to midwater at night (i.e. Beamish, 1966; Turuk, 1973) support this hypothesis. However, movement in the opposite direction has also been observed. Turuk (1973) demonstrated that the direction of the migration is related to the cod diet: when feeding on actively swimming prey, cod descend during the day and ascend at night; if benthic organisms predominate in the diet the opposite is true. Although Pacific cod diet exhibits much diversity, in the study area this species feeds primarily on pelagic fish such as juvenile pollock (Brodeur and Livingston, 1988).

Prohibited species' c.p.u.e. are consistently, although not significantly, higher at night. Higher halibut c.p.u.e. in kg h^{-1} is related to higher proportion of large fish in night catches. We speculate that during the day large fish are more likely to avoid the nets. This is in agreement with the suggestion that vision is the predominant sense used in avoidance reaction when a fish is approached by a trawl (Wardle, 1986). Walsh (1991) demonstrated higher escapement of large flounders (plaice and yellowtail) under the groundgear during the day than during night hours. The night increase in crab c.p.u.e. is consistent with observations of crab podding activity. Dew (1989) reported on diel activity cycles and foraging dynamics of king crab in the general area of this study. We propose that high catch rates at night are generated by fishing when crabs are active and highly aggregated.

Irrespective of the origin of differences in by-catch rate, it is clear that savings may be obtained in the fisheries considered in this study by avoiding fishing during dark hours. Avoiding night fishing may extend the groundfish fishing seasons and increase the harvest of their allowances. From the NORPAC data and information provided by Jerry Berger (pers. comm., NMFS, Seattle), we estimated that for Area 511 the total harvest for Pacific cod and walleye fisheries and the total halibut by-catch are around 50 000 and 500 tonnes respectively. This is about 10% of the entire bottom trawl harvest and halibut by-catch of the Bering Sea. Based on the data from the 1990 fishing season in Area 511, day-only fishing can reduce total halibut by-catch by 13%. Conversely, for the same amount of by-catch taken in the area, day fishing would allow 13% more of the groundfish harvest. Day-only fishing would result in 13% savings of king crab by-catch in numbers, and 16% savings of Tanner crabs. In many instances a change in management strategies designed to protect a particular prohibited species, such as imposing fishing seasons or closing specific areas to harvest, can be to the detriment of other prohibited species. Day-only fishing in the Bering Sea of the fisheries considered, however, appears to reduce concurrently the by-catch rates of Pacific halibut, king crab, and Tanner crabs.

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