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SHORT NOTE

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Digging in the deep: killer whales' advanced hunting tactic

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Abstract We document one of the most spectacular predator-prey interactions observed in a marine ecosystem, in which groups of killer whales force tens of tons of herrring out of their safe deep-water habitat to the surface where the whales are superior. Killer whales performing this hunting tactic congregate in large groups, dive to the limit of their capacity, lift herring vertically more than 150 m by coordinated action, and split large aggregations of fish into small, dense schools before attacking them.

Introduction

Killer whales (*Orcinus orca*) face a challenge when hunting for huge aggregations of herring (*Clupea harengus*), hiding in deep, dark spatial refuges in Norwegian fjords. Every winter, more than 500 killer whales congregate in Lofoten, northern Norway, feeding on adult Norwegian spring-spawning herring (Similä 1997), their main prey throughout the year (Similä et al. 1996). The whole adult population of about 40 billion herring (10 million tons) overwinters in layers, within an area covering only 300–600 km^2, in about 1,000 times higher concentrations than during the ocean feeding period (Foote et al. 1996), forming one of the largest animal aggregations on Earth. Overwintering herring do not feed, and remain deep (160–370 m) during the day in order to minimize predation (Nøttestad and Similä 2001), avoiding sinking through a swim and glide strategy (Huse and Ona 1996). At nighttime they ascend (Huse and Ona 1996), presumably avoiding oxygen depletion (Dommasnes et al. 1994) and swimbladder compression which reduces their buoyancy (Huse and Ona 1996; Nøttestad and Similä 2001). Killer whales seem to depend on daylight to catch herring (Similä and Ugarte 1993; Similä 1997; Nøttestad and Axelsen 1999), and thus face the problem of hunting them in a deep habitat.

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Materials and methods

Using hydro-acoustics, predator-prey interactions between killer whales and herring were monitored in Lofoten (68°18′N 16°02′E) in November with only few hours of daylight. The 16-m research vessel R/V "Fjordfangst" was equipped with FURUNO CH-12 multi-beam sonar (150 kHz) and a PC-based SIMRAD EY-500 (38 kHz) connected to an echo-integrator. The echosounder quantifies swimming depth, vertical extension, density and number of individuals and biomass of a herring school. The killer-whale signals on the echosounder were verified against visual observations at the surface. A colour printer recorded the echosounder signals. The time and position from the navigation log and the global positioning system (GPS) were recorded on the echogram every 120 s. The vessel was located directly above the herring layers under attack by killer whales during the observations, with the propeller disengaged to prevent vessel avoidance.

Results and discussion

Altogether, four observations were made of killer whales hunting on deep layers of herring (Table 1). The whales congregated in large groups of 22–46 individuals, dove to 160- to 180-m depth to penetrate herring layers, and lifted herring aggregations of >25 tons ($\sim$75,000 ind.) to the surface by means of coordinated actions. The whales cut a piece of the deep (>90 m) and extensive ($>1{,}000$ tons $\sim$ 3 million ind.) herring layers, and lifted and packed the fish into dense schools (Fig. 1a). They were, however, only successful twice in herding the fish all the way to the surface. Having isolated the herring vertically from the main layer, the whales split the school into smaller units that were subsequently attacked (Fig. 1b). Hundreds of common gulls (*Larus canus*) and

Table 1 Four observations of killer-whale attacks on deep herring layers

Lifting successful	Bottom depth (m)	Depth range of herring layer (m)	Max. depth of hunting whales (m)	Number of whales (*n*)
Yes	160	90–160	160	22
Yes	170	110–170	170	28
No	405	160–350	180	46
No	420	150–350	170	38

several white-tailed eagles (*Haliaeetus albicilla*) also preyed on the lifted herring.

The average group size was larger than seen in previous observations of killer whales preying on herring schools in more shallow waters (median group size 15, range 6–30, $P < 0.01$, $n = 39$, Mann-Whitney U-test) (Similä et al. 1996). In the two largest groups, herding was preceded by the assembly of three groups of killer whales, which arrived from different locations. Pre-assembly of the whales suggests that they need to operate in large groups to perform this hunting tactic, and that there is communication between groups. In the Pacific, killer whales that feed on small aggregations of salmon usually hunt individually or in smaller groups (Felleman et al. 1991). Modification of group size may be an important factor in the evolutionary arms-race between predator and prey (Dawkins and Krebs 1979; Fernö et al. 1998).

The whales herding the herring layers dove to maximum depths of 160–180 m, and may have approached their maximum diving capacities (Baird 1999; Nøttestad and Similä 2001). Forcing herring from deep waters to the surface demands energy, but enables the whales to attack in shallow water, where there are good light conditions and low ambient pressure. This enables the whales to scare the fish into tight balls (Nøttestad and Axelsen 1999) by means of visual cues (Domenici et al. 2000), such as displaying their white bellies while encircling the school, and to stun fish using tail slaps (Similä and Ugarte 1993; Similä 1997).

In order to prevent the fish from returning to the main layer, whales may depend on lifting large aggregations. In two of four interactions, the whales aborted their deep-diving attacks after 5–10 min, only lifting the herring a short distance. These two herded layers were thinner than those involved in the successful attempts (Table 1). Since schooling fish have strong mutual attraction (Misund 1993; Pitcher and Parrish 1993; Axelsen et al. 2000), where the internal attraction to each other seems to be stronger with increasing number of fish (Vabø and Nøttestad 1997), herding too small concentrations of fish may be unsuccessful. Effective lifting of a layer may also depend on bottom depths

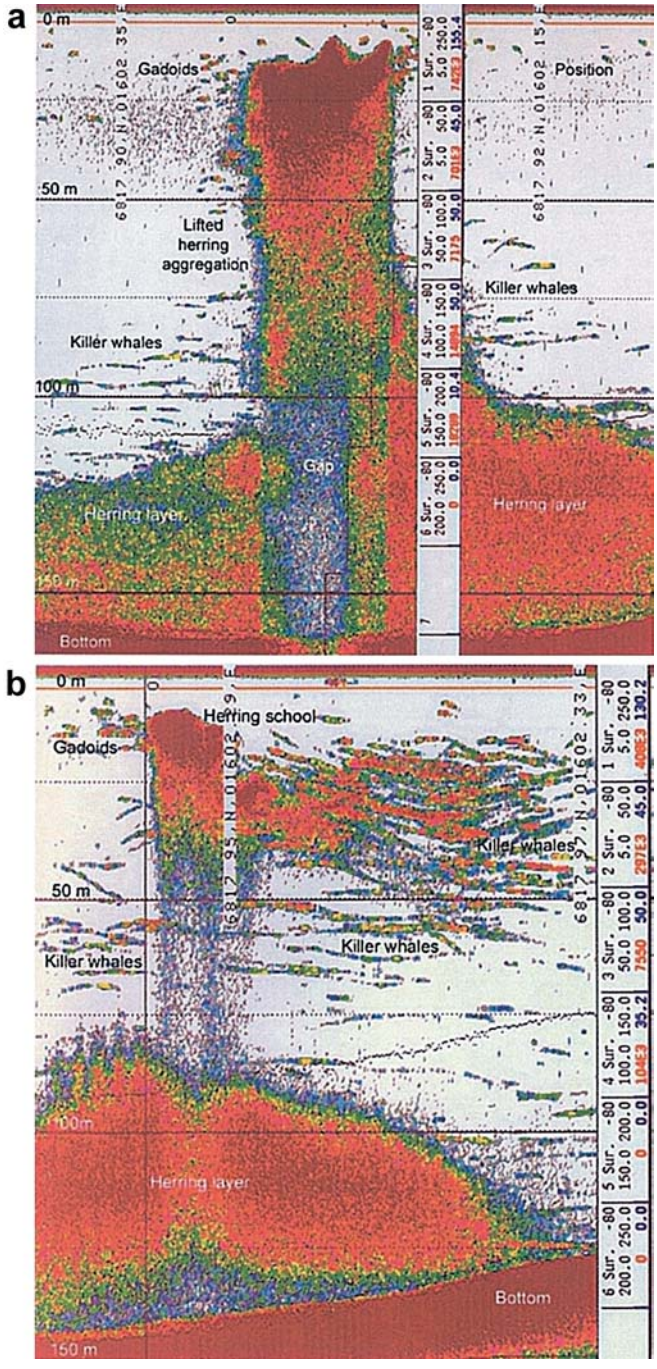

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Fig. 1A, B Killer whales lifting herring. **A** Herring herded from bottom layer to the surface in 6.2 min. Killer whales appear as individual traces surrounding the school. The high concentration of herring in the upper part of the layer being herded illustrates the reluctance of herring to ascend during the day. Gadoids are seen at the upper part of the lifted school. **B** Herring school isolated vertically from main layer under massive whale attack. Fish in the remaining layer closed the gap within 2.5 min. Dense echoes of large numbers of killer whales are seen underneath and beside the herring. Integration tables and integrator lines ($s_A = 0$–$1{,}000$ m^2/n.m^2) are shown on the echograms

< 180 m (Table 1) (Nøttestad and Similä 2001), which would allow the whales to isolate a whole vertical section of the layer and prevent herring from escaping downwards (Fig. 1a). By lifting large concentrations of herring to the surface, whales can trap them in their "fridge" and feed on them repeatedly, while reducing their energy expenditure (Boyd 1997) by using short, shallow dives (Nøttestad and Similä 2001). Nevertheless, hunting for herring in deep water may be difficult and the outcome not certain, even for a large number of cooperating whales.

We suggest that previous observations of killer whales attacking schools of herring in the wintering area (Similä and Ugarte 1993; Similä et al. 1996; Nøttestad and Axelsen 1999) have been preceded by the isolation and herding of herring from deep layers. An intriguing question is what technique killer whales apply to isolate and herd a part of the herring layer from deep water to the surface. Killer whales can be very vocal while hunting (Ford 2002), and frequencies within the hearing capacity of herring might enable the whales to manipulate the fish (see Wilson and Dill 2002). This hunting tactic of digging in the deep, lifting massive amounts of fish all the way to the surface, requires complex social interactions between the killer whales, and could be one of the most advanced hunting tactics ever observed in the marine environment.

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