Behavioral responses of minke whales (*Balaenoptera acutorostrata*) to experimental fishing gear in a coastal environment

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ARTICLE INFO

ABSTRACT

Whale entanglement in fishing gear is a global problem, and underwater ropes associated with this gear are often the cause of injuries that can lead to fatalities. Minke whales (*Balaenoptera acutorostrata*) are especially at risk because they are relatively small, widely distributed, and often occur in coastal habitats where many types of fishing gear are deployed. It is unknown whether minke whales can detect and avoid ropes associated with fishing gear. To address this question we conducted a series of field experiments to measure behavioral responses of nearshore minke whales to underwater ropes simulating crab and whelk fishing gear. We also investigated correlations between whale behaviors and specific environmental variables. Our methods involved both visual and acoustic monitoring of whale behaviors near experimental ropes and buoys of different colors. A remote sensing system was also used to simultaneously monitor oceanographic conditions, record underwater sounds, and capture underwater video of whales swimming near ropes. Minke whales (N=42) decreased their swimming velocity and altered their bearing when passing near experimental ropes, especially during trials with white and black ropes. Some minkes (N=7) also altered their underwater swimming trajectories when passing near ropes, and often appeared to produce low-frequency vocalizations. Collectively this information provides strong evidence that minke whales detect and react behaviorally to the presence of underwater ropes that simulate fishing gear in nearshore areas. We hypothesize that visual and perhaps passive acoustic sensory abilities may be the mechanisms behind these rope avoidance behaviors. We recommend that high contrast ropes (white and black) be used with fishing gear in coastal areas to help minimize entanglements of minke and perhaps other whale species.

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1. Introduction

Entanglement of whales in fishing gear is a serious conservation problem in coastal areas around the world (Perkins and Beamish, 1979; Dayton et al., 1995; Waring et al., 2003; Johnson et al., 2005; Northridge et al., 2010; Song et al., 2010). Minke whales (*Balaenoptera acutorostrata*) are particularly at risk because they are relatively small, widely distributed (Reeves et al., 2002), and often inhabit inshore areas (Horwood, 1990) where many types of fishing gear are located. Their small size, maneuverability, and frequency in shallow water (e.g., <100 m) increase their chances of encountering ropes associated with crab pots, whelk pots, gillnets, and other fisheries gear. Few studies exist regarding minke whale entanglements in fishing gear (Read, 1994) and reasons for this include their high maneuverability, difficulty of individual identification, and missing information from entanglements that go undetected and unreported. Only recently has it been shown that injuries sustained from encounters with ropes often persist and can negatively impact minke whale behavior (Kot et al., 2009).

Minke whales are the second most (15%) reported large whale species entangled in nearshore fisheries gear in eastern Canada where our study took place (Hofman, 1990; Whale Release and Strandings Group, Newfoundland, Canada, unpublished data). These data mostly involved interactions with crab pots, cod traps, and gillnets. Minkes in this area are not considered a species at risk because their current mortality rate does not appear to heavily impact the survival of their local population (Environment Canada, 2010). However, individuals from eastern Canada and the northeast United States are

believed by some to be one population and, if so, combined mortality rates due to entanglements in both areas could be consequential (Hofman, 1990).

There are different uses of ropes with nearshore fishing gear but our study focused on one of the most common — the single buoy line extending from a surface buoy down to gear or systems of gear on the seafloor. These lines are commonly used in eastern Canada and other areas of the western North Atlantic as: 1) buoy lines for single crab, whelk, or lobster pots; 2) end lines in a series of connected pots; and 3) end or anchor lines with gillnet systems. This same type of rope is also used, when legal, as a groundline to connect multiple pots in series along the seafloor. However, testing behavioral responses of whales to groundlines requires a different set of field experiments and is beyond the scope of our study.

Most injurious or fatal entanglements of any whale species are believed to be accidental (Hofman, 1990) but the causes of the initial contact resulting in an entanglement are unclear. Some of these causes may include: 1) difficulty in detecting objects of certain materials and geometries; 2) naiveté with fishing gear and gear design (Hofman, 1990); and 3) sensory abilities negatively impacted by health problems or oceanographic conditions. It is unknown which sensory systems minke whales use to detect and avoid underwater objects, or whether minkes even perceive fishing gear as potentially harmful.

Although the sensory abilities of whales are not well understood, sound is believed to be the primary mechanism for detection and communication (Ketten, 1994). Whereas odontocetes are known to detect underwater objects using echolocation (Miller et al., 2004; Houser et al., 2005; Madsen et al., 2005) baleen whales, such as minkes, are not thought to use echolocation (Au et al., 2001). One study suggests that baleen whales may use acoustic cues (Stimpert et al., 2007) but fishing gear, including ropes and nets, does not appear to generate distinct acoustic signatures at levels allowing easy detection (Leatherwood et al., 1977). Vision in baleen whales is also limited and lacking the ability to discriminate color (Levenson et al., 2000; Peichl et al., 2001). Therefore, it is unlikely that minkes use an active acoustic mechanism or color vision to detect underwater fishing gear but this does not rule out passive acoustic cues.

The objectives of this study were to: 1) conduct behavioral experiments with nearshore minke whales and different colored ropes simulating crab and whelk fishing gear; 2) characterize correlations among behavioral changes near ropes and various environmental variables; and 3) attempt to explain the sensory mechanisms used by minkes to detect and avoid fishing gear. Our aim was to test several working hypotheses involving whether or not minkes would react to the presence of experimental fishing gear, and how fluctuations in tidal conditions and ambient light level might influence the sensory mechanisms that may be involved in gear detection. We quantified different whale behaviors at the surface and also used a remote sensing system to monitor oceanographic conditions, record underwater sounds, and capture underwater video of whales swimming near ropes.

2. Materials and methods

2.1. Experiments and controls

Field experiments were conducted from June–August 2010 in a coastal fishing area within the Mingan Archipelago in the Gulf of St. Lawrence in eastern Canada (near 50° 14′ 49″ N, 64° 11′ 41″ W). Experimental apparatuses consisted of buoys and synthetic ropes of different colors that simulated shallow water crab and whelk fishing gear commonly used throughout the western North Atlantic. Individual ropes were suspended vertically from a 0.31 m (12 in.) diameter Norwegian surface buoy and moored to the seafloor using one of two methods described below. A 2 m grab line with plastic floats and rope loop was attached to the buoy to assist with gear

retrieval into a small boat after each daily trial. Separate trials were conducted for yellow, orange, green, blue, white, and black ropes to test for differences in whale behavior by rope color. These are rope colors commonly used by fishermen in the area. All ropes were 1.5 cm (5/8 in.) in diameter, made of polypropylene, and the standard type used in commercial crab and whelk fishing.

Data for each trial were collected by observers in boats and from a remote sensing system placed on the seafloor adjacent to experimental ropes and buoys. Controls using the same methods were also conducted when experimental gear was not deployed to provide a behavioral baseline to compare with experimental trials. Approach and departure velocities of whales, as well as swim bearing, were calculated relative to rope position during the experiments. The control variables were calculated relative to the median surface position in each series of breaths. This position was chosen because it was consistent with methods used during trials, it was usually the closest position to the ropes, and it provided a consistent spatial delineation between approach and departure data. Only solitary whales exhibiting obvious traveling behavior (defined by Tershy, 1992; Croll et al., 2001) past ropes were included in trials. Those exhibiting other behaviors (e.g., lunge-feeding) were not.

2.2. Remote sensing system

The remote sensing system (Fig. 1) consisted of: 1) five Sony HDR-XR200 video cameras with wide angle lenses (Sony Corporation; Tokyo, Japan); 2) an array of four acoustic recorders (Loggerhead Instruments, Inc.; Sarasota, FL, USA); 3) a depth pressure sensor (Nortek AS; Rud, Norway); 4) a conductivity–depth–temperature probe (CTD; RBR, Ltd.; Ottawa, Ontario, Canada); and 5) a light meter (Thermo Fisher Scientific, Inc.; Pittsburgh, PA, USA). Five, 35 kg steel pods, each containing a video camera inside an Equinox HD 10 underwater housing (Soupcan, Inc.; Galesburg, MI, USA), were constructed to anchor individual ropes. Cameras mounted on the steel pod pointed upward and relied upon ambient light. Pods were used in lieu of actual crab or whelk pots and recorded underwater video of minke whale swimming behavior past each experimental apparatus. Information from the resulting video footage complemented approach velocities, departure velocities, and swim bearings measured at the surface by observers in a boat. Each rope was attached to a pod by a metal safety ring designed to release in the event a whale became entangled during trials.

The pressure sensor and acoustic recorders were moored on the seafloor in early June to continuously monitor oceanographic conditions and biological sounds throughout the summer at the experiment location. These data were used to characterize relationships between tidal velocity and whale behaviors near ropes. These devices were retrieved every three weeks for maintenance and to upload data. Equipment was re-deployed the following day. Deployments of the CTD were conducted from a boat at least once per day. Light measurements were collected every hour because ambient light influences the distance at which marine mammals can visually detect underwater objects (Wartzok and Ketten, 1999). We assumed that absolute changes in ambient light level above the surface were proportional to those below. Tidal harmonic analysis was performed on our pressure data using T-Tide, a set of MATLAB (The MathWorks, Inc.; Natick, MA, USA) programs that analyze tidal characteristics (Pawlowicz et al., 2002). Four main tidal constituents, two diurnal (01, K1) and two semi-diurnal (M2, S2) were found to be significant and accounted for 87% of the original variance. Tidal elevations computed from a tidal prediction model (OTIS, Egbert and Erofeeva, 2002) and the four tidal constituents (01, K1, M2, S2) showed good agreement (within 95% C.I.) with the T-Tide analysis performed on our pressure data. Thus, computation of tidal velocities for our study area was done using the OTIS tidal prediction model.
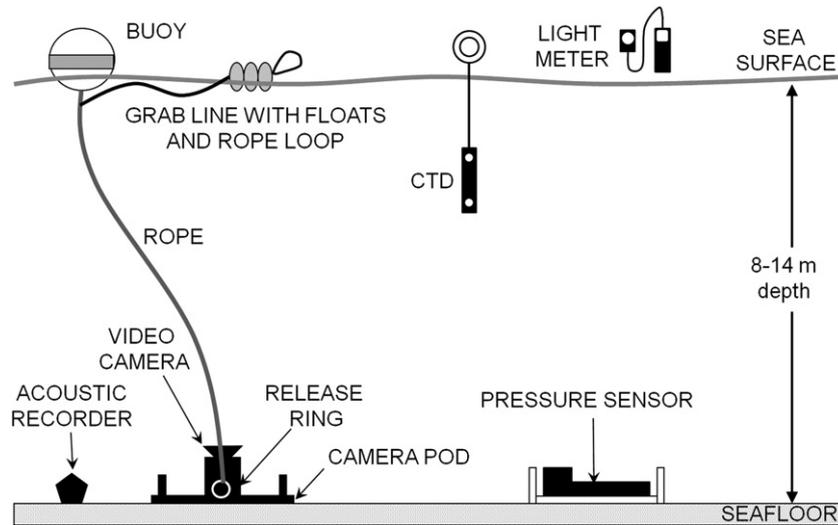
Fig. 1. Remote sensing system components and configuration. An experimental rope connects a surface buoy to a steel camera pod; an array of four acoustic recorders monitors for whale vocalizations; a light meter measures ambient light; and a pressure sensor and conductivity–temperature–depth probe (CTD) measure oceanographic conditions.

2.3. Observations during rope trials

During every morning of effort we deployed a series of five taut and nearly vertical rope systems of the same color, and then conducted experimental trials with passing whales throughout the day. All five rope systems were evenly spaced at 15 m intervals and arranged in a linear series perpendicular to shore from 8 m to about 12 m of depth. This interval was chosen because it was: 1) within the spacing range used for single crab and whelk pots by local fishermen; and 2) it was the maximum distance between adjacent ropes that would fit within each underwater video camera's field of view (when possible, cameras were deployed so their field of view width was parallel to the rope series). On days with exceptionally calm seas we deployed up to ten additional rope systems at the same spacing interval; each of these had a 20 kg weight at the bottom instead of a camera pod. Extension of the series of ropes out to a length of 210 m and a depth of 16 m increased the chances of whales encountering the ropes. Collectively this series of vertical ropes created a "rope fence" (RF) intended to intercept minke whales known to travel along this shoreline during summer months (Naud et al., 2003; Kot, 2009; Kot et al., 2009). After all experimental gear was in place we anchored our boat about 100 m away from one end of the RF to minimize interference with the trials. We then measured distances from the boat to each buoy with a Bushnell Yardage Pro Elite 1500 laser rangefinder (Bushnell, Inc.; Overland Park, KS, USA) and began visual monitoring for approaching whales.

When a minke whale approached within 150 m of our ropes we began monitoring its surface positions (during breaths) relative to the RF and then collected digital photographs for individual identification using a telephoto lens on a digital SLR camera. The global positioning system (GPS) coordinates of each surface position were determined by entering the whale's distance (measured with the rangefinder) and compass bearing from our stationary boat into GPS Visualizer software (www.gpsvisualizer.com). This procedure allowed us to calculate positions as each whale approached, passed through, and departed from the RF (Fig. 2). Maps containing each series of surface positions, the stationary buoy positions, and a reference scale were then created for each trial using Google Earth software (www.google.com/earth). Each map was uploaded into ImageJ freeware (http://rsb.info.nih.gov/ij) so distances and bearings between whale positions, and distances from whales to the RF, could be measured. Knowing times and distances between whale positions allowed us to calculate: 1) approach and departure velocities $(m \cdot s^{-1})$ relative to the RF; 2) approach and departure bearings (°)

relative to the RF; and 3) changes between each after crossing the RF. This same protocol was used to generate information for all trials with each color of rope. Standard photographic identification techniques (Hammond et al., 1990) were used to determine sample sizes for all experiments. These were necessary for statistical analysis of data and to ensure that individual whales only took part in the experiments once, thereby maintaining the same level of naiveté toward the RF.

After the field season a team of six research assistants scanned the underwater video footage for sequences of whales passing near ropes. When whales were captured on video, 10 s segments were imported into Adobe Premiere Pro software (Adobe Systems, Inc.; San Jose, CA, USA) for still frame extraction. Digital landmarks were placed on subjects within each frame to trace their swimming trajectories relative to the rope position on a pixel grid (each video frame = 480 × 720 pixels) using ImageJ freeware. See Zeidberg (2004) and Kot et al. (2009) for a more complete description of these videogrammetric techniques.

Prior to conducting parametric statistical tests, normality of all data was tested using a Kolmogorov–Smirnov test. If normality was not met data were transformed. All statistical tests were conducted using SPSS 17 (SPSS, Inc.; Chicago, IL, USA). A one-way analysis of variance (ANOVA) was used to test for differences in swimming
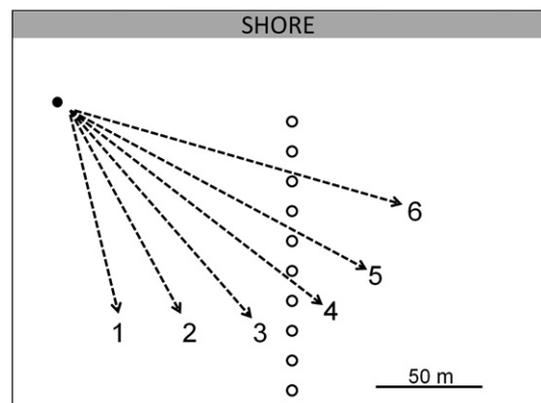

Fig. 2. Linear configuration of experimental rope systems (open circles) relative to shore. Numerals indicate a typical series of whale surface positions when passing through the rope fence ("RF" throughout the text). Arrows indicate distances measured with a laser rangefinder from our stationary boat (closed circle) to each surface position. Distances plus compass bearings allowed calculation of each surface position's GPS coordinates.

velocity and bearing during experimental trials and controls. General linear model (GLM) regressions were used to predict correlations between whale approach and departure velocities based on their distance from ropes. The same models were used to predict correlations between differences in velocity and bearing for each rope color across natural variations in tidal current velocity and ambient light level. Chi Square analyses were used to test for statistically significant differences ($P<0.05$) between vocalizations produced when minke whales were near the RF and away from the RF.

3. Results

3.1. Velocity changes

Minke whales markedly decreased their swimming velocity when passing through or near the RF. The difference between approach and departure velocity mean values was -0.53 ± 0.15 m s^{-1} ($P<0.05$, F = 6.6, ANOVA, N = 42; Table 1). Regression analysis demonstrated a positive correlation between whale approach velocity ($R^2 = 0.54$, N = 42; Fig. 3A) and departure velocity ($R^2 = 0.56$, N = 42; Fig. 3B),

Table 1
Experimental trials: whale identification (ID), approach velocity (AV), departure velocity (DV), velocity change (ΔV), approach bearing (AB), departure bearing (DB), bearing change (ΔB); rope color (C), yellow (Y), orange (O), green (G), white (W), black (Bk), and blue (Be); left or right (L/R).

ID	C	AV (m·s^{-1})	DV (m·s^{-1})	ΔV (m·s^{-1})	AB (°)	DB (°)	ΔB (°)	L/R
Ba1	Y	2.6	0.59	−2.01	127.20	105.70	21.50	L
Ba2	Y	1.9	0.97	−0.93	300	316.7	16.70	R
Ba3	Y	3.1	1.4	−1.7	312.30	305.80	6.50	L
Ba4	Y	1.9	1.09	−0.81	95.4	297.1	201.70	R
Ba5	Y	2.26	1.88	−0.38	270.2	301	30.80	R
Ba6	Y	2.27	2.7	0.43	147.3	106.6	40.70	L
Ba7	Y	1.09	1.16	0.07	184.7	305.7	121.00	R
Ba8	O	2.99	2.24	−0.75	153	117.5	35.50	L
Ba9	O	2.6	2.7	0.1	104.7	120.8	16.10	R
Ba10	O	3.6	2.7	−0.9	44.3	165.7	121.40	R
Ba11	O	1.7	0.57	−1.13	126.3	105.7	20.60	L
Ba12	O	2.7	1.9	−0.8	5.55	9.5	3.95	R
Ba13	O	2.1	0.98	−1.12	105.9	138.1	32.20	R
Ba14	O	1.57	2.2	0.63	132.7	2	130.70	L
Ba15	O	0.96	0.5	−0.46	347.4	302.1	45.30	L
Ba16	G	1.1	2.43	1.33	310.6	255.7	54.90	L
Ba17	G	2.7	1.4	−1.3	237.4	339.1	101.70	R
Ba18	G	3	1.86	−1.14	206.6	168.4	38.20	L
Ba19	G	2.6	2.3	−0.3	278.6	359.1	80.50	R
Ba20	W	0.73	0.70	−0.03	134.8	74.1	60.70	L
Ba21	W	0.64	0.54	−0.1	312	253.7	58.30	L
Ba22	W	3.7	1.7	−2	122.4	114	8.40	L
Ba23	W	5.5	1.9	−3.6	80.6	107.2	26.60	R
Ba24	W	1.47	1	0.47	280.6	273.7	6.90	L
Ba25	W	0.54	0.4	0.14	250.8	70.6	180.20	L
Ba26	W	1.28	0.86	−0.42	55.9	73.6	17.70	R
Ba27	Bk	3.77	3	−0.77	123.3	104.9	18.40	L
Ba28	Bk	2.28	2.5	0.22	295.6	310.4	14.80	R
Ba29	Bk	1.78	1.8	0.02	138.4	117.2	21.20	L
Ba30	Bk	2.31	2.14	−0.17	132.8	115.8	17.00	L
Ba31	Bk	1.27	1.06	−0.21	97.2	272.2	175.00	R
Ba32	Bk	1.88	2	0.12	291.4	339.7	48.30	R
Ba33	Bk	1.06	0.88	−0.18	161.7	106.1	55.60	L
Ba34	Bk	1.35	2.5	1.15	330.1	255.1	75.00	L
Ba35	Bk	2.93	3.12	0.19	314.3	345	30.70	R
Ba36	Bk	4.3	1.35	−2.95	172.8	154.3	18.50	L
Ba37	Bk	1.94	1	−0.94	14	254.8	240.80	R
Ba38	Bk	1.37	1.6	0.23	148.2	118.1	30.10	L
Ba39	Be	0.42	1.54	1.12	267.8	289.5	21.70	R
Ba40	Be	1.61	1.39	−0.22	287.8	272.7	15.10	L
Ba41	Be	1.37	1.24	−0.13	113.7	97.2	16.50	L
Ba42	Be	3.07	1.59	−1.48	100.6	88.3	12.30	L
Mean ± SE				−0.53 ± 0.15			54.8 ± 8.7	

and distance from ropes. That is, whale velocity decreased upon approach and increased upon departure. A positive correlation was demonstrated between whale approach velocity and distance from ropes for all colored ropes, with white ropes showing the strongest correlation ($R^2 = 0.76$, N = 7; Fig. 4D). Black ropes showed the strongest correlation ($R^2 = 0.74$, N = 12; Fig. 4E) between whale departure velocity and distance from ropes. Control results showed a difference between mean approach and departure velocities of -0.10 ± 0.40 m s^{-1} ($P>0.05$, F = 0.04, ANOVA, N = 21; Table 2), an 81.1% decrease compared to the difference between mean approach and departure velocities when ropes were present during experimental trials. We also demonstrated a negative correlation between whale velocity versus tidal flow velocity across the RF when whales swam against the tidal flow ($R^2 = 0.42$; N = 17; Fig. 5), but no correlation was shown when whales swam with tidal flow. There was also no correlation between whale velocity versus surface light level (lx) when passing most ropes of different colors. However, the correlation between whale velocity versus surface light level was relatively high for white ropes ($R^2 = 0.79$, N = 7; Fig. 6A) and black ropes ($R^2 = 0.54$, N = 12; Fig. 6B).

3.2. Bearing changes

Minke whales altered their swim bearing when passing through or near the RF. The difference between approach and departure bearing mean values was $54.8\pm8.7°$ ($P<0.05$, F = 16.8, ANOVA, N = 42; Table 1), with black ropes showing the highest mean bearing difference ($91.4\pm20.7°$). Regression analysis for whale bearing changes versus distance from ropes was not conducted because bearing changes occurred close to individual ropes. The difference between mean approach and departure bearing change during controls was $21.2\pm2.7°$ ($P>0.05$, F = 0.07, ANOVA, N = 21; Table 2), 61.3% less than when ropes were present. A small but positive correlation

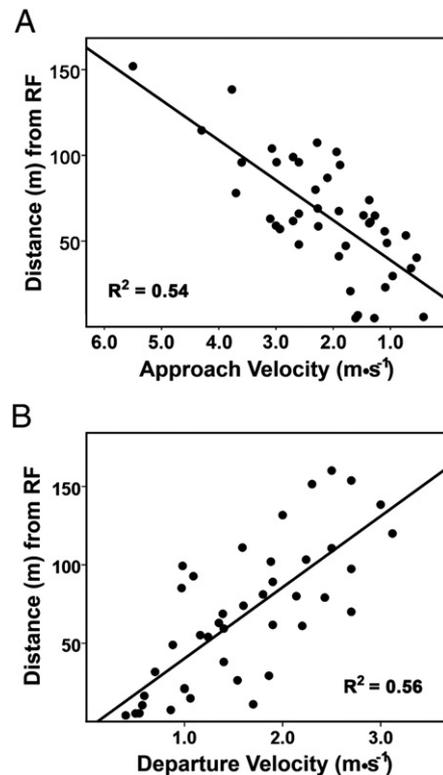**Fig. 3.** (A) Regression analysis demonstrating a positive correlation between whale approach velocity (m·s^{-1}; N = 42) and distance (m) from the RF (X-axis data are shown in reverse order). (B) A positive correlation demonstrated between whale departure velocity (m·s^{-1}; N = 42) and distance (m) from the RF.
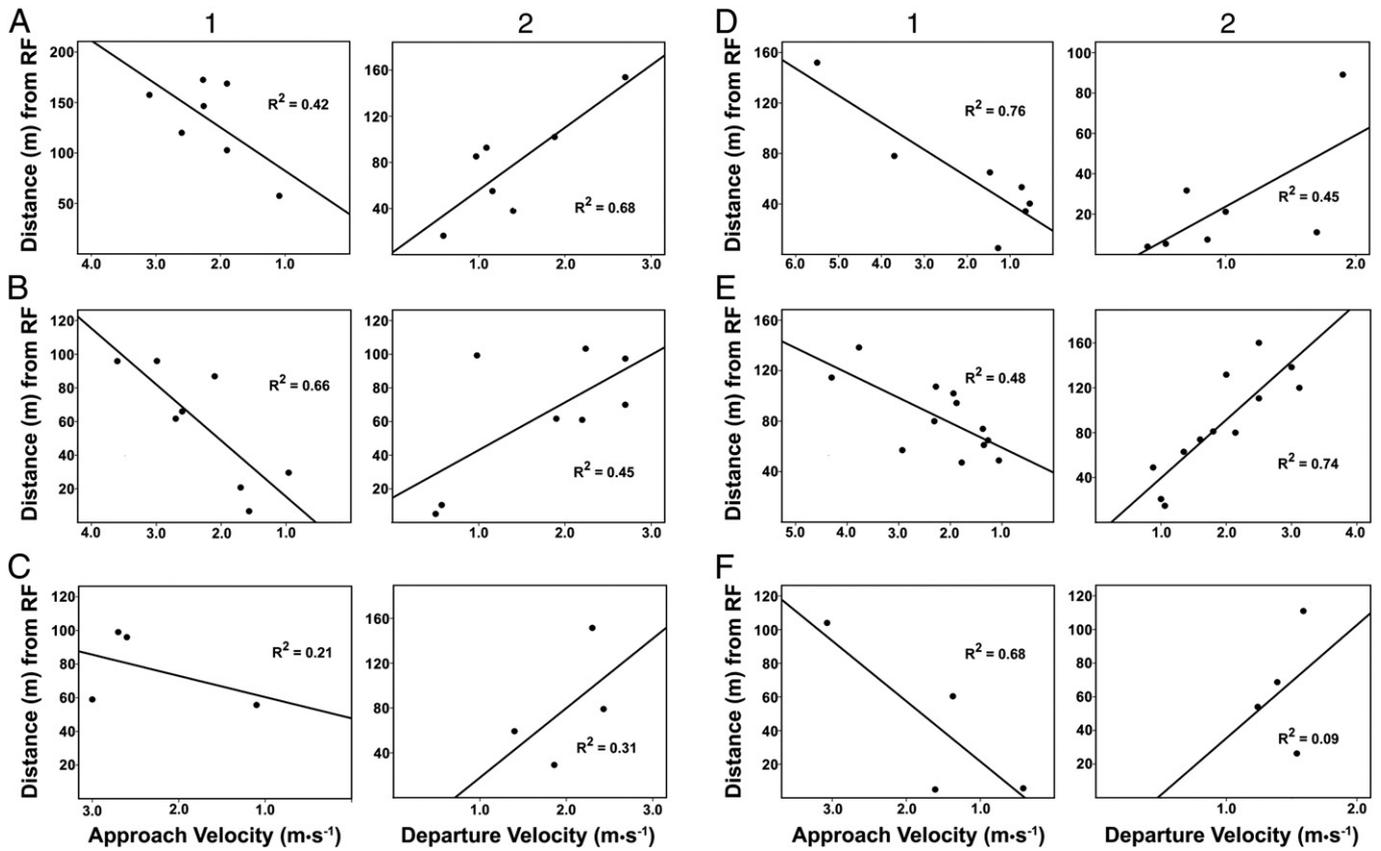
Fig. 4. Regression analysis demonstrating a positive correlation between whale approach velocity ($m·s^{-1}$; column 1; X-axis data are shown in reverse order) and departure velocity ($m·s^{-1}$; column 2), and distance from ropes (m) for yellow (A), orange (B), green (C), white (D), black (E) and blue (F) ropes.

between whale bearing change and tidal flow velocity was also shown when whales were swimming against tidal flow ($R^2 = 0.25$; N = 15; Fig. 7), but no correlation was observed with tidal flow. No correlations were detected between mean bearing change and surface light level when whales passed all colors of rope. Total counts

for turning direction near the ropes were 18 right and 24 left during experiments (Table 1), and 13 right and 8 left during controls (Table 2). A Chi Square analysis did not show statistically significant differences between right and left turns during experiments or controls, indicating that behavioral lateralization was not a factor when whales changed swimming directions.

3.3. Underwater swimming trajectories near ropes

Results from underwater video provided behavioral reactions of seven minke whales to the RF at depth and out of view from observers in the boat. Tracing of underwater trajectories showed parabolic pathways away from or around the ropes for all seven whales (Fig. 8). The combination of above and below water behavioral responses of minke whales to ropes provides strong evidence that subjects detected the ropes and made subsequent
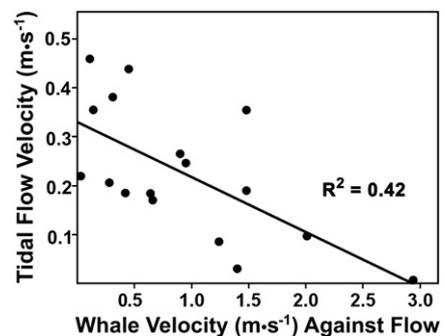
Table 2
Controls: whale identification (ID), approach velocity (AV), departure velocity (DV), velocity change (ΔV), approach bearing (AB), departure bearing (DB), bearing change (ΔB); left or right (L/R).

ID	AV ($m·s^{-1}$)	DV ($m·s^{-1}$)	ΔV ($m·s^{-1}$)	AB (°)	DB (°)	ΔB (°)	L/R
Ba43	1.8	1.83	0.03	68.5	56.1	12.4	L
Ba44	3.81	3.48	−0.33	83.3	74.3	9	L
Ba45	5.58	4.94	−0.64	118.24	146.65	28.41	R
Ba46	2.13	2.44	0.31	350	8.52	18.52	R
Ba47	2.94	2.55	−0.39	89.3	91.3	2	R
Ba48	3.69	4.89	1.2	152.3	164.9	12.6	R
Ba49	5.32	1.64	−3.68	42.3	21.7	20.6	L
Ba50	3.7	1.67	−2.03	302.6	332.5	29.9	R
Ba51	2.21	0.72	−1.49	8.49	47.7	39.21	R
Ba52	3.82	1.81	−2.01	41.3	31.7	9.6	L
Ba53	2.1	2.22	0.12	6	335.7	30.3	L
Ba54	3.46	2.05	−1.41	217	250.2	33.2	R
Ba55	2.96	2.8	−0.16	142.1	172.4	30.3	R
Ba56	2.36	4.94	2.58	314.5	337.3	22.8	R
Ba57	1.66	5.2	3.54	335.7	324.3	11.4	L
Ba58	1.93	0.89	−1.04	71.7	47.5	24.2	L
Ba59	2.67	2.24	−0.43	205.6	169.9	35.7	L
Ba60	3.57	7.28	3.71	318	5.1	47.1	R
Ba61	3.85	3.01	−0.84	190.8	193.1	2.3	R
Ba62	4.08	2.85	−1.23	142.2	155.3	13.1	R
Ba63	3.53	5.68	2.15	264	298.9	34.9	R
Mean ±			−0.10 ±			21.2 ±	
SE			0.40			2.7	

Fig. 5. Regression analysis demonstrating a negative correlation between whale velocity ($m·s^{-1}$) change and tidal flow velocity ($m·s^{-1}$) when whales swam against tidal flow (N = 17).
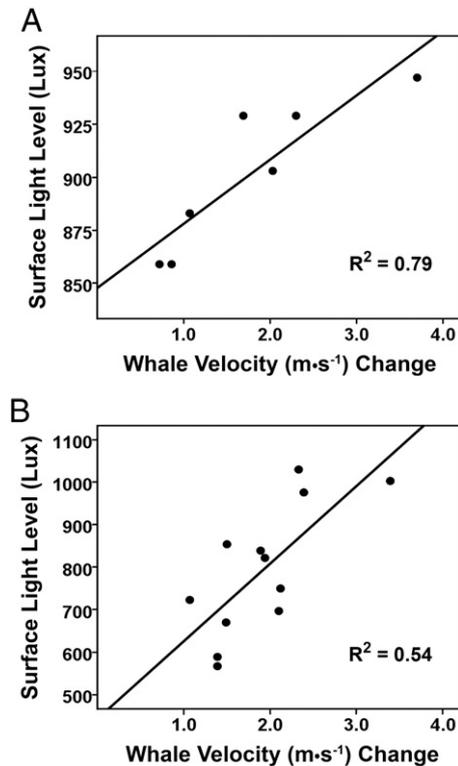
Fig. 6. Regression analyses demonstrating two positive correlations between whale velocity change $(m \cdot s^{-1})$ and surface light level (lx) when whales passed white ropes (A, N = 7) and black ropes (B, N = 12).

behavioral changes to avoid them. No evidence of physical interaction between whales and ropes was captured on video or observed at the surface.

3.4. Vocalizations near ropes

Our acoustic equipment repeatedly recorded sounds that have features consistent with minke vocalizations (Fig. 9). These vocalizations occurred when eleven different minkes were observed passing through or near the RF. Due to an equipment failure we were not able to localize whale vocalizations. However, the highest intensity sounds were recorded when subjects were <118 m from the recorders. The frequency range of the predominant energy of these vocalizations was 40–500 Hz (N = 98), with a mean pulse duration of 0.47 ± 0.015 s, a mean pulse interval of 0.58 ± 0.04 s, and a range of 1–12 pulses per group. Mean distance from our boat to whales was 169 ± 14.6 m (40–400 m; N = 42). Synchronization of sound
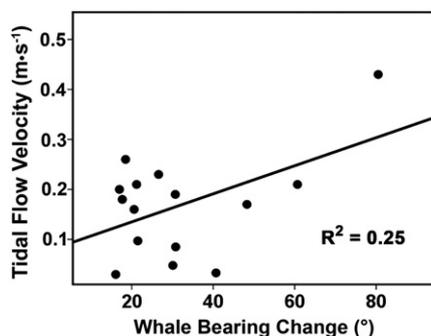

Fig. 7. Regression analysis demonstrating a positive correlation between whale bearing change (°) and tidal flow velocity $(m \cdot s^{-1})$ when whales were swimming against tidal flow (N = 15). Bearing data are shown as absolute values.
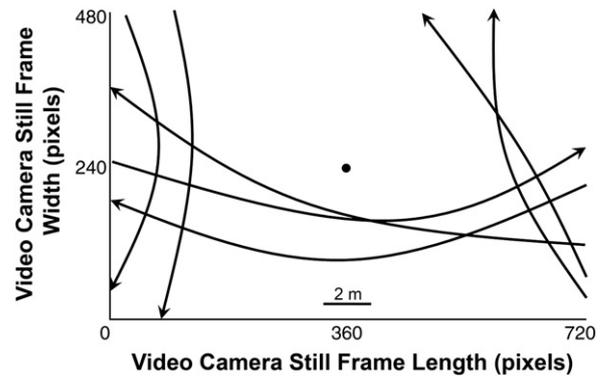

Fig. 8. Video camera still frame showing underwater swimming trajectories (arrows) of minke whales passing an experimental rope (closed circle).

recordings with our observations of whales near the ropes indicates that minke whales were the source of these sounds. Chi Square tests also demonstrated a statistically significant difference between vocalizations recorded when minkes passed within 10 s of the ropes as opposed to when they were more than 10 s away (Fig. 10; $X^2 = 13.78$, P<0.001, N = 18, d.f. = 17).

4. Discussion

Minke whales in our study area clearly demonstrated the ability to detect fishing ropes and avoid physical contact with them. Behavioral reactions by whales supported our hypotheses that minkes would decrease velocity and alter their swimming direction near the RF. Why whales altered their velocity and swim bearing with oncoming tidal flow is unclear, although this may be related to the effects of hydrodynamic drag on swimming locomotion and maneuverability. Our analysis of ambient light properties of shallow water provides evidence that minkes may visually detect ropes at close range, and that certain colors of rope may be easiest to see in variable lighting conditions. We did not find evidence of passive acoustic detection of ropes because our acoustic recordings did not include any rope-generated sounds. However, it remains a possibility that rope flow noise may be an acoustic cue allowing rope detection, especially during moderate to strong tidal flow regimes. If so, these cues could be masked at times by both natural and anthropogenic background noise (e.g., strong surf zone and vessel traffic). Although few ships pass through our remote study area, other coastal areas where baleen whales regularly encounter heavy shipping traffic (e.g., right whales *Eubalaena glacialis* near Boston, MA, USA; Knowlton and Kraus, 2001) could be difficult for acoustic detection of ropes associated with fishing gear.

4.1. Visual detection: rope hues and ambient light levels

This study provides evidence that minkes may visually detect ropes, and that white and black ropes may be easier to detect. These two colors are hues at the extremes of the monochromatic range in which whales see (Levenson et al., 2000), and contrast most with natural background hues during daylight periods (Fig. 11; also see "contrast hypothesis" in Peichl et al., 2001). This suggests that whales are less at risk of entanglement in dark and light ropes during the day. Whether this risk increases at night, when light availability is about six orders of magnitude less than during the day (Wartzok and Ketten, 1999), is outside the scope of this study. Some marine mammals are believed to use vision primarily during low light levels (Dawson, 1980; Levenson and Schusterman, 1999) but it is possible that passive acoustic abilities assist rope detection under these low visibility conditions.
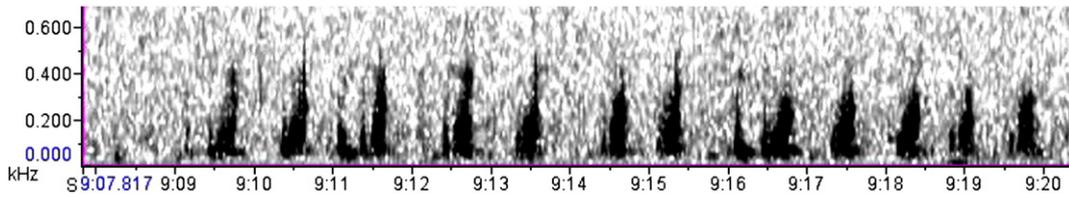
Fig. 9. Typical low frequency sound structure (40–500 Hz) and pattern recorded when eleven minke whales passed ropes during experimental trials. This sound type is similar to those from known minke whale vocalizations in other areas (see text for references).
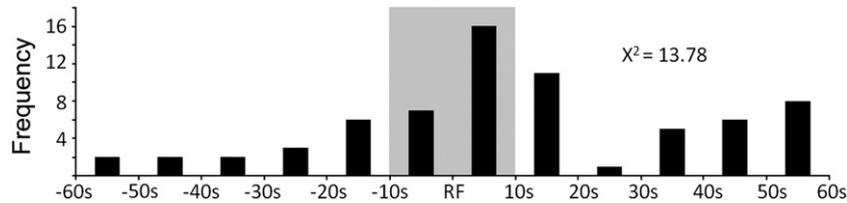

Fig. 10. Frequency distribution of minke whale vocalizations as subjects approached, passed through, and departed the RF. Total counts per 20 s bins are shown from 60 s before to 60 s after individual whales (N = 18) passed through or near the RF. Shaded area represents a statistically significant increase of vocalizations when whales were <10 s before and after passing the RF.

4.2. Potential for passive acoustic detection: tide-generated rope flow noise

Ropes with size and material properties similar to those used in our study are known to vibrate in water currents and generate noise-producing turbulence that changes in proportion with flow velocity magnitude (Charnews, 1971). Despite the lack of obvious rope flow noise on our recorders, it is reasonable to expect that water currents vibrated our ropes and may have produced an acoustic signal and level that was proportional to the magnitude of tidal flow. We hypothesize that minkes may use passive acoustic sensory capabilities under tidal flow conditions strong enough to vibrate ropes, and have begun further investigations to assess any potential sounds emitted from our experimental ropes.

Presumably, the recorder array would have detected sounds produced near and far from the RF. Interestingly, our results indicate that vocalizations occurred most often when whales passed the RF. The same minke whale vocalization signature was recorded when eleven whales were observed passing the ropes, though it is not clear if acoustic or visual detection of ropes stimulated their vocal responses. These low-frequency patterns are generally similar in structure to minke whale vocalizations in other geographical areas though their function is unknown (Schevill and Watkins, 1972; Winn and Perkins, 1976; Leatherwood et al., 1981; Edds-Walton, 2000; Mellinger et al., 2000; Gedamke et al., 2001).
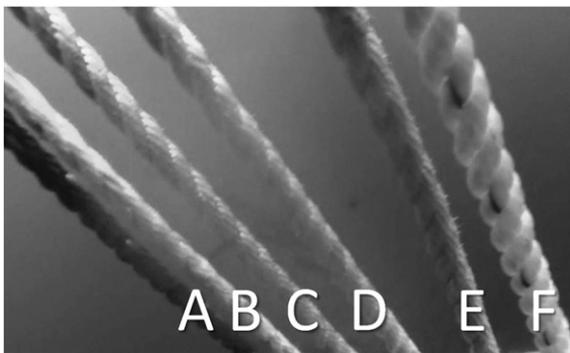
4.3. The entanglement problem

If minke whales can detect and avoid underwater ropes then why is there widespread prevalence of living whales with rope-like injuries, and stranded whales entangled in fishing gear (i.e., ropes; Perkins and Beamish, 1979; Kot et al., 2009; Song et al., 2010)? It is possible that minkes inhabiting coastal fishing areas learn to avoid fishing gear after a few encounters, or that rope entanglements result from preoccupation during different types of behavior such as lunge-feeding. Song et al. (2010) showed that the majority (~80%) of fatally entangled minkes in the East Sea of Korea had recently fed. Johnson et al. (2005) also showed that 77.4% of entangled right whales and 47% of entangled humpback whales considered in their analysis had ropes attached to their mouths. This would suggest that minke whale entanglement may occur during forceful lunge-feeding events, when their attention may be directed toward engulfing schools of prey in close proximity, rather than other man-made objects in their environment. Oceanographic and sea-state conditions are likely to contribute to the problem. During our study minkes were able to detect and avoid simulated fishing gear likely using vision and perhaps passive acoustics during conditions of moderate current flows and sea-state, but their capability for detection of fishery gear may be compromised during weather fronts, unusually strong current flow, and at night or under low light conditions.

Our results suggest additional experimental investigations are necessary to better understand the causes of whale entanglements in fishing gear. Future work in this area should include both visual and acoustic properties of ropes, with the aim of exploiting these signals by developing inexpensive gear modifications that could increase the ability of whales to detect them. Such modifications would decrease risks to whales while maintaining gear efficacy. Future experiments should include ropes of different diameters and employ a diversity of deployment set-up configurations (including floating and sinking groundlines), as well as those with add-on devices that enhance the acoustic and visual presence of ropes to passing whales. A comparative study into color vision would help design field experiments testing for colors of fishing gear that are most easily detected and avoided. The most useful studies should include tests conducted at night or during low light periods, one of the least studied topics in this area of research. These efforts could use dataloggers, night vision technology, and acoustic recorders to better understand the importance of natural light in detection and avoidance of gear by whales.

Fig. 11. Grayscale video still frame of black (A), blue (B), green (C), yellow (D), orange (E) and white (F) ropes at 5 m of water depth, an approximate mid-water column location. Differences in hue and contrast with the background are evident.

We recommend that fishermen and policy makers use gear that contrast best with backgrounds in their fishing areas, and that white, black, or even white and black striped ropes, be used in coastal areas where minke whales are abundant. However, solutions to the global whale entanglement problem include knowing how different whale species detect and react to different types of coastal and offshore fishing gear. Behavioral experiments similar to those in this study and by others (e.g., Kraus and Rolland, 2007; right whales) should be conducted with other mysticete and odontocete whale species to gain a more complete understanding of the widespread risks and impacts of fishing gear to whales in different areas of the ocean. Minkes may react best to fishing gear made of white and black ropes but further testing is required to determine how, if at all, other large whale species may react to gear of these colors.

Acknowledgments

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