Project 4 Final Report

Assessments of Vision to Reduce Right Whale Entanglements

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Introduction

The North Atlantic right whale (*Eubalaena glacialis*) is the most endangered large whale in the north Atlantic, with less than 500 alive today. Population growth is impaired by high levels of human-caused mortalities (Kraus and Rolland, 2007). At least 50% of all deaths in this population are caused by human activities, primarily ship collisions and entanglements in fisheries gear (Cassoff et al, 2011; Moore et al., 2004). Despite management efforts, entanglement rates remain high, and may claim at least one North Atlantic right whale annually along the east coast of North America (Knowlton and Kraus, 2001). Approximately 82% of the animals in the Right Whale Catalog carry scars caused by ropes or nets (Knowlton et al., 2012). Fixed fishing gear is distributed very broadly along the coast of North America, and all types of fixed fishing gear have been recovered from entangled right whales (Johnson et al., 2005; 2007).

As the right whale-gear entanglement problem continues, the failure to solve it jeopardizes the viability of several fixed gear fisheries, especially the lobster fishery (Van der hoop et al., 2012). This work was to determine if the color or visible features of ropes could provide whales a visual deterrent, thereby averting entanglements. It sought to identify those visual characteristics which might be used in rope construction to help whales avoid entanglements.

Methods

The purpose of this experiment was to determine whether changing the visual characteristics of rope mimics in the path of skim-feeding right whales alters the distance at which whales respond by exhibiting a change in behavior. Researchers studying right whales suspect that vision is a critical mode of sensory perception for prey detection and navigation. Cetaceans have adapted well to the spectral properties of a variety of aquatic photic environments, with light-gathering and enhancement mechanisms, high levels of resolution acuity, and special pupillary and retinal mechanisms to adjust to different light levels allowing for vision both above and below the water surface. Fasick et al (2011) estimated the spectral sensitivities of the right whale rod and cone visual pigments (493 nm and 524 nm, respectively) and found that these estimates would allow the rod and cone photoreceptors to be tuned in a way that optimizes photon capture in an extremely light-limited environment. While the photoreceptors are tuned to a region of the spectrum to detect underwater background light, they are insensitive to wavelengths greater than 650 nm, or the red region of the visible spectrum. In this situation, red objects in the water column produce a perfect high-contrast dark silhouette against the bright background light in either the horizontal or upward visual axes.

Although a wide variety of colors are used in fishing ropes, there is a strong preponderance of greens and blacks in fixed gear lines. Based on the early work by Fasick et al (2011) and Kot et al (2012), this experimental work is designed to determine if changing color or the visual characteristics of rope elicits changes in behavior that might be employed to enhance a whale's ability to avoid entanglements by detecting and maneuvering around such ropes.

We constructed 20-foot rope mimics from two 10 ft sections of rigid PVC pipe approximately the same diameter as 1" rope. The two sections were connected with quick release snap clips, and the entire length was mechanically scored every 2 to 3 inches so that they would shatter if a whale touched them. Ropes were weighted at one end, and attached to a lobster buoy at the other, so that during deployment, whales were presented with the equivalent of a vertical rope in the water column. Each rope mimic lobster buoy was fitted with a 30.5 cm disk oriented horizontally in order to have a fixed measurement reference in any still or video images collected by the observers. We originally planned to try 3 rope colors and one illuminated rope. However, based upon information on whale vision and the fixed gear fishery, additional colors were built. Ropes were painted with a variety of colors, including two that are common in most fisheries (black and green), two types of white rope (one white paint, and one glow in the dark white/green paint), and two colors that appear to occur in the spectral sensitivity for right whales (orange and red) that results in extremely high contrast (Figure 1). In 2012, we also developed and tested ropes with flashing or steadily illuminated LED's, although the LED failure rate was so high that this avenue of work was abandoned.

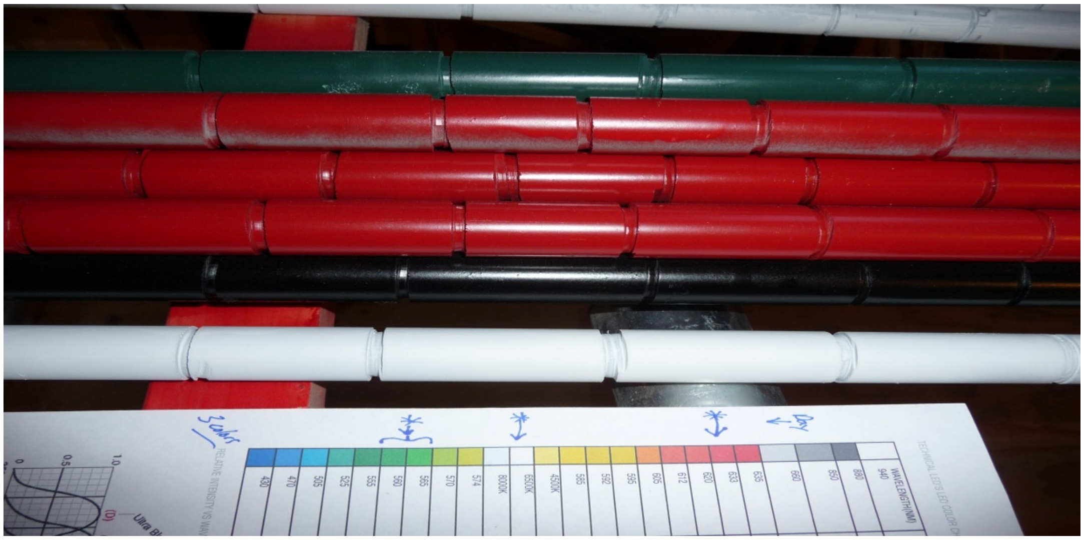

Figure 1. *Selection of ropes constructed for the experiment (not all colors shown).*

The tests occurred in Cape Cod Bay, where multiple right whales sometimes skim-feed along the depth contour lines off of Herring Cove. Surface-feeding whales were chosen because their behavior was continuously visible and it was possible to estimate their trajectories in advance to facilitate placement of the rope mimics. In addition, because the whales were presumably distracted (or focused on) by feeding, this is a robust test to determine responses. In other words, for visual stimuli to be effective, they must be detectable (and the whale must respond) when the whale is busy doing something else.

In both years, as whales encountered the rope mimics (defined as an approach by a whale to a "rope" within 10 m, the limits of underwater visibility), a variety of behaviors occurred. Initially, we believed that the measurement of significance would be changes in swimming direction, and we planned to conduct paired trials of each "rope" color. However, the challenges of working in brief suitable weather conditions, as well as the variability and unpredictability of whale behavior, caused us to change the experimental design by deploying multiple ropes in a row to maximize the probability of encounters. In addition, since all encounters were recorded with HD video, we were able to evaluate all response behaviors, including directional changes, respiration rate changes, submergence events and durations, swimming cessation/change in fluke beat, and tail flicks, for each whale that approached a rope-mimic. In the analysis, any change in behavior as the whale approached the rope mimic indicated that it had seen the rope and was responding. We measured the distance between the "rope" and the whale as it approached, as well as the distance between the two as the whale exhibited its first response using repeated readings taken from a laser range finder, still images of the whale approaching each rope mimic buoy with the reference disk, and the HD video recordings. All analyses were applied to the distance between the whale and the rope mimic at the first change in visible behavior.

We used the M/V Junet, a 42 (12.9m) foot motor yacht with an inboard diesel and a flybridge for this experiment. In 2011, rope "mimics" were deployed from the stern of the M/V Junet as the vessel crossed right whale feeding paths perpendicular to their trajectory, well in advance of the whales passage (ca 75 – 150 m). The M/V Junet then stopped and shut down, so the observers were off to the side of the feeding path (Figure 2), and observations were made of all encounters between the rope mimics and right whales. After the whales passed by, ropes were retrieved and re-deployed as conditions allowed. Deployment of the "ropes" in this fashion led to a straight line of rope mimics with 30 m to 40 m intervals between each rope (Figure 3). Since underwater visibility was measured at 10 m or less, this ensured that whales encountering a rope mimic would be confronted with only a single visual stimulus. However, it also meant that a right whale travelling through the exact middle of an inter-rope interval would be unlikely to see either rope.

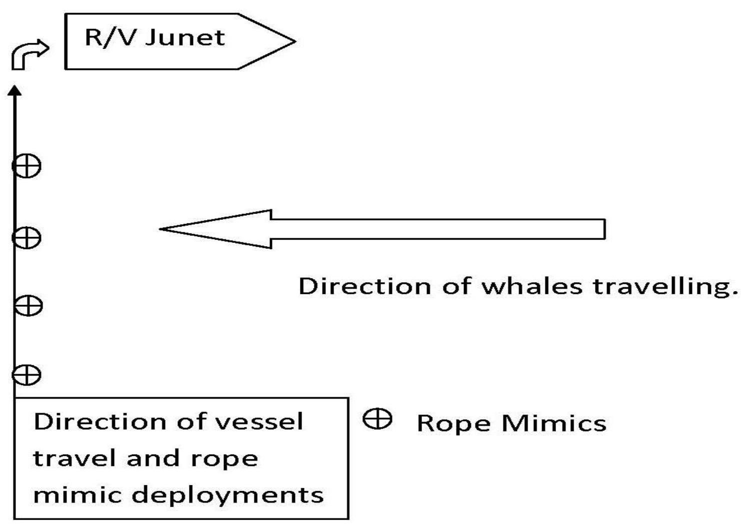

Figure 2. *Diagram of 2011 experimental design for testing whale responses to rope mimics.*

Figure 3. *An experimental linear deployment of fake ropes in 2011. The right whale in the background (heading left) swam outside the furthest rope mimic.*

In 2012 we changed the method of rope mimic deployment. Because the 2011 deployment strategy required the vessel to cross in front of the whales at large distances (ca 100 m), we had no ability to control the probability of an encounter once the ropes were deployed, as approaching whales could swim through the array, or turn around, or change swimming directions long before reaching the experimental area. In addition, there was a small (albeit unlikely) chance that the passage of the M/VJunet could disrupt the aggregations of plankton that the whales were feeding on, possibly leading to changes in behavior related to the change in plankton density, and not to the rope mimics. To eliminate this possibility, and to better control both the deployment locations and the probability of encounters, we used a modified 40" radio controlled electric catamaran to tow the rope mimics into place. This eliminated potentially confounding variables, including ship noise and movements that might have affected whale behavior, as the M/V Junet could stay silent during the entire trial period. This strategy was highly successful, enabling precise deployments with a greatly reduced risk of disturbance.

The primary consideration of "rope" color selection was the experimental power in testing different rope color/types. For example, in 2011, rope mimic colors (red, white, black, and green) were deployed randomly on each set (see Figures 1 and 2). Unfortunately, because of the relatively few encounters and the variability of the whale movements around the deployments, no encounters between whales and red "ropes" occurred in 2011. In addition, we discovered using underwater cameras that the white "ropes", (both the glow in the dark white and the straight white paint) became invisible at relatively close distances. For these reasons, the work in 2012 focused on collecting data on encounters between whales and red or orange “ropes”, with limited (and unsuccessful) attempts to use the LED “ropes”.

In 2011 we used night vision equipment to determine the effects of rope mimics on right whale behavior at night on two nights. We used a FLIR Thermosight ATWS Block Infrared imaging system and a U.S. Military night-vision light-intensifying scope to track and film whales. During both nights, as the sun set, skim feeding behavior ceased, and no skim-feeding was subsequently observed despite tracking for several hours. Since skim feeding behavior was essential to track whale responses to rope-mimics, the change in whale behavior meant the no rope mimics were deployed around whales at night. No further efforts were made to follow whales at night.

This research was conducted under NMFS Permit (No 15415), issued to Scott D. Kraus for this specific research activity, valid through March 31, 2014.

In addition to this fieldwork, a literature review of sea turtle vision was conducted to ensure that colored or illuminated ropes would not have a negative effect on sea turtles (Appendix 6). The visual spectrum sensitivity range of the right whale appears to overlap with those of several sea turtle species. No studies have shown any particular color to be attractive or repulsive to sea turtles. Lights have been shown to attract juvenile loggerhead turtles, while experiments to reduce green turtle bycatch in gillnets have used LED lights and chemical light sticks to successfully prevent entanglements.

Results

The M/V Junet launched out of Plymouth, MA, and most work was done between Chatham and Herring Cove (west of Provincetown) along the eastern side of Cape Cod Bay, although in 2012, we worked a few skimfeeding whales on the northeastern side of the Cape. In both years, weather hindered operations, as any wind above 12 knots would move the observation vessel too rapidly downwind to remain stationary relative to the rope mimic deployments. Nevertheless, we managed to work 5 days in 2011 and 6 days in 2012. Not all of these days involved working around whales, because right whales sometime feed in linear patterns (which provided good experimental conditions), but sometimes were observed feeding in random, or circular and unpredictable patterns. In the latter case, no deployments were made, because we could never be certain whether a whale’s turn was related to a rope mimic or a change in copepod patch distribution. At the conclusion of both years, we had three days with whale/rope encounters in 2011 and 2 days with whale rope encounters in 2012 (Table 1).

Table 1. A summary of the deployments, encounters, conditions, and rope color.

Date	Start Time	End Time	Position	Sea State	Cloud Cover	Wall Orienta -tion	Order of Rope Colors	Total # Egs Passed Through
4/7/2011	1802	1826	42 0.1, 70 7.6	2	0%	NE-SW	B, R, W, G	1
4/7/2011	1839	1900	42 0.4, 70 8.4	2	0%	NE-SW	B, W, G	2
4/8/2011	1334	1417	42 2.3, 70 8.1	2	75%	E-W	R, G, W, B	4
4/8/2011	1524	1547	42 1.8, 70 7.9	1	100%	E-W	R, G, W, B	3
4/14/2011	1611	1633	42 1.9, 70 13.0	1	50%	NE-SW	B, G, B, G	17
4/14/2011	1633	1655	42 1.7, 70 13.0	1	50%	NE-SW	W, W	2
4/14/2011	1704	1730	42 1.2, 70 12.3	1	50%	N-S	W, W, G/B, G	1
4/14/2011	1740	1758	42 1.5, 70 12.6	1	50%	NE-SW	W, W, B, B	1
4/14/2011	1813	1835	42 1.2, 70 12.2	1	50%	NE-SW	W, W, G/B, G	1
4/14/2011	1924	1933	42 3.0, 70 14.0	1	50%	NE-SW	W, W, B	3
3/20/2012	1605	1615	42 2.8, 70 14.2	1	0%	n/a	R	3
3/20/2012	1636	1644	42 2.8, 70 14.1	2	0%	n/a	R	1
3/21/2012	959	1005	42 1.76, 70 13.0	2	30%, fog	n/a	R	1
3/21/2012	1009	1020	42 1.76, 70 13.0	2	30%, fog	n/a	R	2
3/21/2012	1038	1055	42 2.0, 70 12.8	2	30%, fog	n/a	R	1
3/21/2012	1130	1200	42 2.15, 70 13.15	1	30%, fog	n/a	O	1
3/21/2012	1206	1235	42 2.36, 70 13.31	1	30%, fog	n/a	O	4
3/21/2012	1332	1422	42 2.5, 70 13.58	1	30%, fog	NW-SE	R, G	7

Data analysis focused on the distance at which the first visible change in behavior occurred. Because the data were non-parametric and consisted of small sample sizes, only strong reactions were measured. The identifications of reactions were based upon observations of the whale's antecedent behavior, videotaped and and/or observed for up to 3 minutes before the encounter between the whale and the rope mimic (Figure 4). Reactions included noticeable changes in direction, submergence, closing the mouth, cessation of respiration, and change in fluke beat (Figure 5). The preliminary analysis showed a significant difference in the distance of first change of behavior by right whales confronted with black and green ropes (n=8, mean distance = 2.625 m) vs red and orange ropes (n=7, mean distance = 6.21m) (Mann-Whitney U Test=55.5, p = 0.0018) (see Table 2).

Figure 4. *Right whale approaching a rope mimic before any change in behavior.*

Figure 5. *The same whale showing a change in behavior (submergence and slight acceleration from the ripples at the tail) as it passes by the rope mimic.*

Table 2. Analysis of distances at which the first change in a whale's behavior occurred in response to an encounter with a rope mimic.

Date	Time	Camera Time	Secchi (ft) over Water Depth (ft)	Lighting	Color of rope	Min Est. Distance from Rope (m)	Eye distance from rope at first rxn	Mean	Variance	SD
4/7/2011	1808	2:00	n/a	back lit	B	2	2	2.625	0.76786	0.876275
4/14/2011	1617	1:13	14/14	front lit	G	2.5	2.5			
4/14/2011	1617	1:24	14/14	back lit	B	0	2.5			
4/14/2011	1618	2:42	14/14	back lit	G	2	3			
4/14/2011	1619	3:09	14/14	back lit	G	2.5	3			
4/14/2011	1619	3:42	14/14	front lit	G	1.5	4			
4/14/2011	1624	8:15	14/14	back lit	G	2	3			
4/14/2011	1624	8:16	14/14	back lit	G	0	1			
3/20/2012	1609	6:30	25/25	front/side	R	3	5.5	6.2143	1.65476	1.286375
3/20/2012	1637	9:00	25/25	front/side	R	5	6			
3/21/2012	1048	9:00	20/20	backlit	R	5	6			
3/21/2012	1150	23:53	20/20	backlit	O	3	7			
3/21/2012	1211	28:39:00	20/20	backlit	O	5	7			
3/21/2012	1217 (b)	33:38:00	20/20	backlit	O	3	4			
3/21/2012	1217 (f)	39:29:00	20/20	front	O	6	8			

The underwater visibility was measured with the vertical drop of a Secchi disk, and in all cases the visibility exceeded the distance at which the first changes in behavior were observed. In most of the locations where whale/rope encounters were recorded, the underwater visibility extended to the bottom (Table 2). When we did secchi readings in deeper waters, the underwater visibility was approximately 10 m in both years. However, on one occasion, we lowered an underwater camera to collect visibility in the horizontal plane, and that distance appeared to be somewhat less than the traditional vertical Secchi measurement, possibly due to the way in which sunlight illuminated particles in the water near the surface.

We recorded whether the direction of how the rope appeared illuminated (from the front or behind) for each whales' approach (Table 2). There was no significant difference in behavioral response distances between illumination characteristics (front or backlit) ($p = 0.28$, t-test with unequal variances), although sample sizes are small.

Night Vision Work

On two nights we attempted to conduct this experiment after sunset under extremely low-light condition (no moon). The night vision equipment worked well, enabling observations of right whales at night. The infrared camera provided relatively low resolution images that made the whales appear white (warm) against a black (cold) background (Figure 6a and b). Blows were visible at nearly ½ a mile, but the ability to identify individuals was compromised by the poor resolution. The military light intensifying scope had better resolution, and the green phosphor images were in some cases adequate for individual whale identifications (Figure 6c and d).

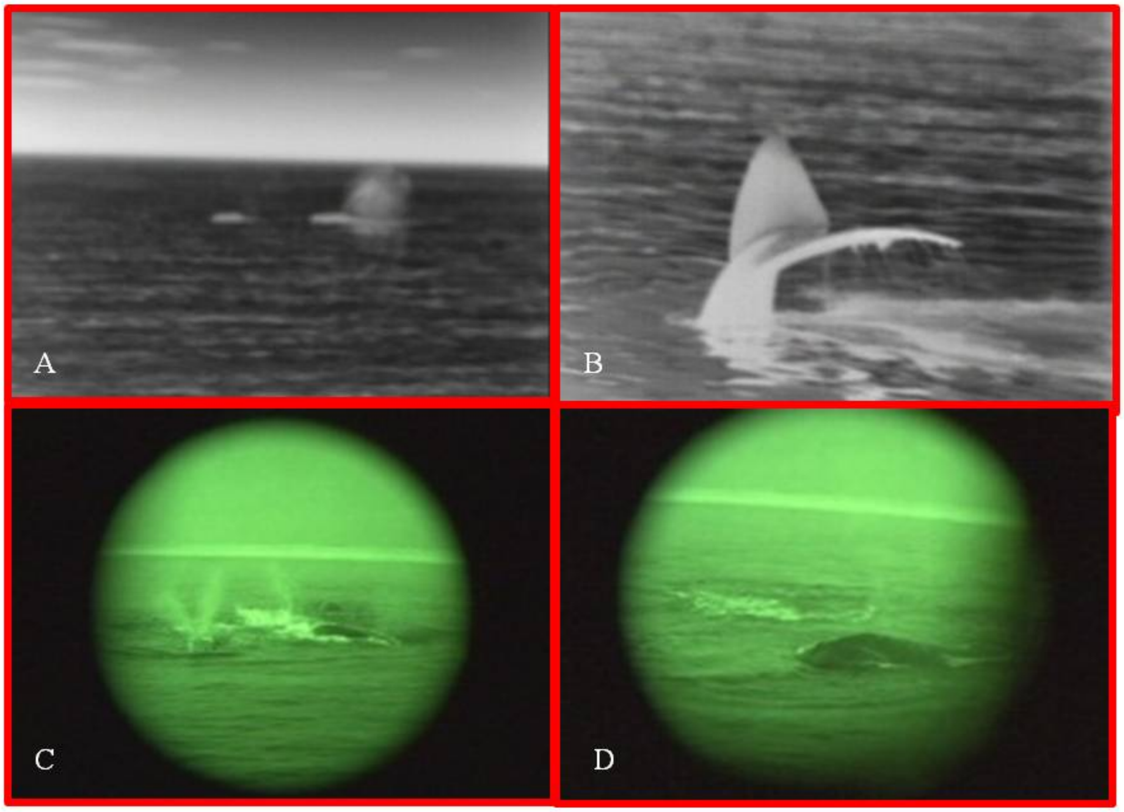

Figure 6. *Night vision images taken on April 14th 2011 between 2000 and 2100 hours (sunset was at approx 1840). A) Infrared image of distant blow. B) Infrared image of right whales flukes. C) Light intensifying image of right whales courtship group. D) Light intensifying image of right whale head.*

However, on the two days we attempted to continue the rope mimic tests into the evening, right whale behavior changed as the sun set. Skim feeding at the surface ceased, making it impossible to conduct the experimental trials, and the whales initially dispersed. Using the night vision equipment, we followed the whales to determine if skim feeding might occur later in the evening. Instead, no skim feeding was observed, and some right whales started socializing (Figure 5-6C), while others started deeper dives (Figure 5-6B). No skim feeding was observed for the rest of the evening, and observations ceased around midnight. After two nights of observations with similar behavior changes, no further attempts were made to conduct rope-mimic trials at night.

Outreach

The details and results of this work have been presented in public on three occasions. The PI gave talks at the Gulf of Maine Research Institute summer speaker series in Portland Maine, and at the Bigelow Labs Café Scientifique speaker series in Boothbay Harbor, Maine, in August of 2012. In addition, more technical results of this work were presented at the North Atlantic Right Whale Consortium in New Bedford, MA November of 2012.

Discussion

This experimental work proved extremely challenging, with weather, whale behavior, and technical issues all reducing appropriately controlled encounters between whales and rope mimics. Despite 11 days and two nights at sea, sample sizes for different rope color datasets were very small. Nevertheless, despite the small sample sizes, there appears to be a significant difference in the distance of first changes in behavior between whale encounters with black/green ropes and red/orange ropes. Had these differences been slight (e.g. on the order of 20% difference, we would not have had the statistical power to demonstrate any differences. However, the appearance of strong differences in behavior in these circumstances suggests a real phenomenon in right whales visual detection capabilities.

The spectral sensitivity of the right whale rod visual pigment has recently been directly determined (Bischoff et al., 2012), and is shown in Figure 7. The *E. glacialis* rod visual pigment is tuned to a region of the spectrum to detect underwater background light but appears insensitive to wavelengths greater than 600 nm. The primary prey species of the North Atlantic right whale, the calanoid copepod *Calanus finmarchicus*, transmits light in the red region of the visible spectrum. Microspectrophotometric measurements of the *C. finmarchicus* carotenoid pigments show light transmission profiles that are nearly the inverse of the spectral sensitivities of the *E. glacialis* rod visual pigment, effectively blocking light between 450 and 550 nm while transmitting light maximally at wavelengths greater than 600 nm. Therefore, right whale prey, *C. finmarchicus* would produce a perfect high-contrast dark silhouette against the bright background in either the horizontal or upward visual axes. In this experiment, the red and orange ropes produce reflected light that occurs in the red portion of the spectrum, and may have created a higher contrast image than all other colors, thereby allowing right whales to detect those “ropes” at a greater distance.

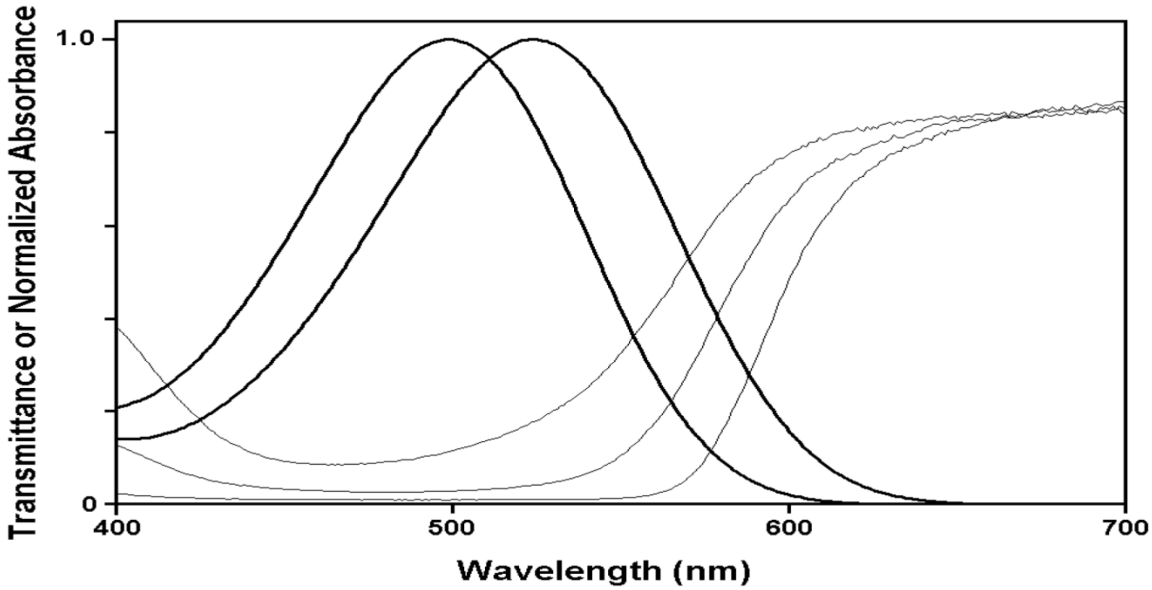

Figure 7. *Right Whale Visual Pigment Absorbance Spectra & C. finmarchicus Oil Pigment Transmission Spectra.*

Conclusion and Next Steps

In conclusion, this work provides strong evidence that changing the colors of rope used in fishing gear may improve whales' ability to detect and avoid those ropes under daylight conditions. However, the small sample sizes used in the comparative analysis call for caution, and further work is needed. This project will continue for at least one more year with funding from NMFS Bycatch Reduction Engineering Program, in an attempt to double the sample sizes, to refine our experimental techniques and methods, and to get robust answers to the question of whale vision and entanglement probabilities.

References Cited

Bischoff, NM, Nickle, B, Cronin, TW, Velasquez, S, Fasick, JI. 2012. Deep-Sea and Pelagic Rod Visual Pigments Identified in the Mysticete Whales. Visual Neuroscience 29(2): 95-103.

Cassoff RM, Moore KM, McLellan WA, Barco SG, Rotstein DS, Moore MJ. 2011. Lethal entanglement in baleen whales. Disease of Aquatic Organisms 2011 96:175-185

Fasick, J.I., Bischoff, N., Brennan, S., Velasquez, S. & Andrade, G. (2011). Estimated absorbance spectra of the visual pigments of the North Atlantic right whale (*Eubalaena glacialis*). Marine Mammal Science 27, E321–E331.

Johnson, A.J., S.D. Kraus, J.F. Kenney, and C.A. Mayo. 2007. The Entangled Lives of Right Whales and Fishermen: Can They Coexist? Pp 380- 408 *In*: Kraus, S.D. and R.M. Rolland (Eds.) 2007. The Urban Whale: North Atlantic Right Whales at the Crossroads. Harvard University Press. Cambridge, Massachusetts. 543 p.

Johnson, A., G. Salvador, J. Kenney, J. Robbins, S.D. Kraus, S. Landry, and P. Clapham. 2005. Fishing gear involved in entanglements of right and humpback whales. Marine Mammal Science 21(4): 635-645.

Kot, B.W., R. Sears, A. Anis, D. P. Nowacek J. Gedamke, C. D. Marshall. 2012. Behavioral responses of minke whales (Balaenoptera acutorostrata) to experimental fishing gear in a coastal environment. Journal of Experimental Marine Biology and Ecology 413 (2012) 13–20.

Kraus, S.D. and R.M. Rolland (Eds.) 2007. The Urban Whale: North Atlantic Right Whales at the Crossroads. Harvard University Press. Cambridge, Massachusetts. 543 p.

Knowlton, A.R. and S.D. Kraus. 2001. Mortality and serious injury of northern right whales (*Eubalaena glacialis*) in the western North Atlantic Ocean. J. Cetacean Research and Management, Special Issue 2:193-208.

Knowlton A.R., P. K. Hamilton, M. K. Marx, H. M. Pettis, S. D. Kraus. 2012. Monitoring North Atlantic right whale *Eubalaena glacialis* entanglement rates: a 30 yr retrospective. Mar. Ecol. Prog. Series 446:293-302.

Moore MJ, Knowlton AR, Kraus SD, McLellan WA, Bonde RK (2004) Morphometry, gross morphology and available histopathology in North Atlantic right whale (*Eubalaena glacialis*) mortalities (1970–2002). J. Cetacean Res. Management 6: 199–214

Van Der Hoop, M. J. Moore, S.G. Barco, T.V.N. Cole, P. Daoust, A.G. Henry, D.F. McAlpine,W.A. Mclellan, T. Wimmer, and A.R. Solow. 2012. Assessment of Management to Mitigate Anthropogenic Effects on Large Whales. Conservation Biology, Volume **, No. *, 1–13. DOI: 10.1111/j.1523-1739.2012.01934.x