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Seabird bycatch mitigation and blue-dyed bait: A spectral and experimental assessment

Lisa J. Cocking^{a,d}, Michael C. Double^{a,e,*}, Peter J. Milburn^b, Vittorio E. Brando^c

^aSchool of Botany and Zoology, Australian National University, ACT 0200, Australia

^bJohn Curtin School of Medical Sciences, Australian National University, ACT 0200, Australia

^cCSIRO Land and Water, GPO Box 1666, Canberra ACT 2601, Australia

^dAustralian Fisheries Management Authority, P.O. Box 7051, Canberra, ACT 2610, Australia

^eAustralian Antarctic Division, 203 Channel Highway, Kingston, Tasmania 7050, Australia

ARTICLE INFO

Article history:

Received 27 July 2007

Received in revised form

18 February 2008

Accepted 11 March 2008

Available online 28 April 2008

Keywords:

Longline fishing

Pelagic crypsis

Albatrosses

Petrels

Shearwaters

ABSTRACT

The application of blue-dye to fishing baits is a seabird bycatch mitigation technique used in some pelagic longline fisheries that is thought to make the baits less visible and hence less attractive to seabirds. We tested this assumption in two ways. First, by measuring the spectral profiles of blue-dyed baits (fish and squid) and modelling the spectral profiles of the ocean under set conditions, we assessed how well wedge-tailed shearwaters (*Puffinus pacificus*) can distinguish dyed baits based on the known visual characteristics of this species. Results showed that no baits were perfectly cryptic against the background ocean, and only blue-dyed squid were relatively cryptic both in terms of chromatic and achromatic contrasts. Second, during at-sea trials blue-dyed and non-dyed baits that were simultaneously presented submerged on a longline or as surface presentations. During 26 longline sets which presented squid only, a 68% reduction in interactions with blue-dyed squid was observed compared to non-dyed squid. During surface presentations only 3–8% of blue-dyed squid baits were struck over the duration of the study compared with 75–98% of non-dyed squid bait. When using fish baits, however, approximately 48% of all blue-dyed baits presented in the first two days of trials received strikes from seabirds but this increased to 90% over the last three days. These results suggest the use of blue-dyed squid bait could decrease seabird bycatch in pelagic longline fisheries whereas blue-dyed fish baits are less likely to have a mitigatory effect.

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1. Introduction

The incidental catch (or bycatch) of seabirds has been reported in trawl, driftnet, and gillnet fisheries but has been associated with longline fisheries in particular. The magnitude of seabird bycatch in some longline fisheries is such that population models link a decline in some seabird populations and bycatch

rates in nearby fisheries (Hall et al., 2000; Tuck et al., 2001; Weimerskirch et al., 1997). Presently 61 species of seabirds are recognised as being affected by longline fishing; 25 of which are threatened with extinction (Gales et al., 1998; Gilman, 2001). Procellariiform seabirds such as albatrosses, petrels and shearwaters are particularly at risk of being caught on longlines because of their mode of foraging behaviour (Baker

* Corresponding author. Address: Australian Antarctic Division, 203 Channel Highway, Kingston, Tasmania 7050, Australia. Tel.: +61 3 6232 3407.

E-mail addresses: Lisa.Cocking@afma.gov.au (L.J. Cocking), Mike.Double@aad.gov.au (M.C. Double), Peter.Milburn@anu.edu.au (P.J. Milburn), Vittorio.Brando@csiro.au (V.E. Brando).

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doi:10.1016/j.biocon.2008.03.003

et al., 2002; Gales et al., 1998). These birds strike at baits, usually during line-setting, and sometimes get hooked and drown when the line sinks (Baker et al., 2002; Gilman et al., 2005; Tuck et al., 2001). In addition, large, aggressive species such as the wandering albatross (*Diomedea exulans*) may become hooked or tangled when taking baits from diving birds returning to the surface (Baker et al., 2002; Gales et al., 1998).

Catch rates of seabirds in longline fisheries are highly variable (e.g. Baker and Wise, 2005; Gales et al., 1998; Ryan et al., 2002; Weimerskirch et al., 2000) and are thought to be influenced by environmental conditions including light levels, sea surface conditions, bird abundance, moon phase, and season (Gomez Laich et al., 2006; Weimerskirch et al., 2000) as well as location and whether the longline is set to sink to the seafloor (demersal) or to remain pelagic (Alexander et al., 1997). Mitigation techniques that aim to reduce seabird bycatch include modifications to fishing patterns (e.g. night setting and seasonal area closures), bird deterrents (e.g. lights, sound and water) and techniques that reduce access to baits (streamer line, side-setting, weighted lines, underwater setting chutes and bait capsules, e.g. Boggs, 2001; Gilman et al., 2003; Gilman et al., 2005; Lokkeborg, 2003; Minami and Kiyota, 2006). The efficacy of these techniques varies between fisheries and fishing vessels, and some fishers are reluctant to employ some deterrents because they are seen to be deleterious to catch rate, inconvenient, dangerous, costly, or the long term economic benefits are not immediately apparent (Gilman et al., 2003; Hall et al., 2000; Minami and Kiyota, 2004b, 2006).

Blue-dyed bait is a seabird bycatch mitigation technique that has been used in the Hawaiian, Brazilian and Japanese pelagic longline fleets (Baird, 2001; Gilman et al., 2003; McNamara et al., 1999; Minami and Kiyota, 2001). It is assumed that the blue-dye reduces the contrast between the baits and the surrounding seawater making it more difficult for seabirds to see and strike the baits (Gilman et al., 2003). Previous research on the use of blue-dyed bait has been fisheries-based and shows either a mitigatory or undetectable effect on seabird bycatch rates. However, this research is difficult to assess because it has largely been documented in reports to fishery management organisations where data and analyses are not necessarily presented in full (Boggs, 2001; Gilman et al., 2003; Lydon and Starr, 2004; McNamara et al., 1999; Minami and Kiyota, 2001; Minami and Kiyota, 2004a; Minami and Kiyota, 2006).

To date, no studies have examined the spectral properties of blue-dyed baits or quantified how seabirds might perceive the dyed baits. Instead, it is assumed that if dyed baits appear less visible to the trichromatic vision of humans then it is likely that this will also hold for birds that have higher visual acuity and tetrachromatic vision (Lydon and Starr, 2004; Lythgoe, 1979; Maier, 1992). Using information on the spectral properties of the bait and the ocean, and the specific visual acuities of seabirds, it is possible to predict whether blue-dyed baits are visible in the ocean using species-specific visual models (Vorobyev and Osorio, 1998). By combining visual models with at-sea trials, this study aimed to determine: (1) whether blue-dyed fish and squid baits are theoretically less apparent to seabirds; and (2) whether dyeing baits blue can significantly reduce bait-strikes during at-sea trials.

2. Methods

As far as we are aware, the wedge-tailed shearwater (*Puffinus pacificus*) is the only procellariiform species for which retinal spectral sensitivities data are available (Hart and Vorobyev, 2005; Hart unpublished data). We therefore based our spectral analyses on these data and also conducted field trials where this species was commonly encountered. However, visual pigments are highly conserved among related bird species (Hart, 2001), therefore it is likely that the results from our discriminability model are applicable to other procellariiform species such as the congeneric flesh-footed shearwater (*Puffinus carneipes*). This species was also recorded frequently during our at-sea trials, and is also known to be impacted by longline fishing operations (Baker and Wise, 2005).

2.1. Bait reflectance (R^{bait})

To prepare the blue-dyed baits, the squid (*Nototodarus gouldi*) or fish (*Sardinops neopilchardus*) were completely thawed and then soaked in a 0.5% aqueous salt water solution of Brilliant blue food dye (C.I. 42090, E133, Australian Food Ingredient Suppliers) for 20 min. The dye solution was then completely drained from the baits. Reflectance spectra of non-dyed and blue-dyed baits were measured using an Ocean Optics S2000 spectrometer coupled with a PX-2 pulsed xenon light source. Measurements were taken relative to an Ocean Optics WS-1 white standard. The probe was fitted with a tubular case cut at a 45° angle to ensure measurement angles were constant for all readings. All readings were taken with the casing of the probe touching the bait, following Endler (1990). Five separate baits were measured for both non-dyed and blue-dyed fish and squid. For each squid bait, ten readings were taken from the mantle and ten from the head. For fish baits, ten readings were taken from the dorsal surface and ten from the ventral surface. The spectrophotometer was recalibrated between each bait. The data were pooled and averaged across all individuals within each group in order to obtain one indicative spectrum for the six treatments (non-dyed and blue-dyed for squid; non-dyed and blue-dyed dorsal and ventral surfaces of the fish).

2.2. Calculating background ocean reflectance

For a bait to be cryptic, its reflectance spectra must have low (almost zero) inherent contrast to the ocean background after accounting for the visual acuities of the observer. Such reflectance spectra (R^{cryptic}) can be calculated using Eq. (1) (corresponding to Eq. (2.6) of Johnsen, 2002), where $E(\lambda)$ is the downward irradiance of a particular wavelength λ at the bait's surface, and $L_b(\lambda)$ is the upward radiance of the background ocean. This equation assumes the bait in the water is being viewed directly from above

$$R^{\text{cryptic}}(\lambda) = \frac{\pi L_b(\lambda)}{E(\lambda)}, \quad (1)$$

Irradiances ($E(\lambda)$) and background radiance ($L_b(\lambda)$) were estimated using Hydrolight (Mobley and Sundman, 2001), a radiative transfer software package which accurately predicts underwater radiance distributions under specified environ-

mental conditions (Johnsen, 2002; Mobley et al., 1993). This program requires the following input: depth of measurement, solar elevation and azimuth angle, atmospheric conditions, sea conditions, chlorophyll content and chlorophyll fluorescence and Raman scattering. Four Hydrolight simulations were run with the input values shown in Table 1. These conditions were selected to approximate those found in open ocean Case 1 waters (Jerlov and Nielsen, 1974), the water class where most longline fishing occurs (Loisel and Morel, 1998). For these four sets of environmental conditions radiance and irradiance values were generated at depths of zero (just below the sea's surface) and 15 m and then used to calculate R^{cryptic} . These two depths were chosen as they closely resemble the depth of baits in at-sea trials during this study (see below).

2.3. Visual modelling

The ability of a seabird to distinguish between the reflectance from a bait (R^{bait}) and the ocean background (R^{cryptic}) is dependent on both the chromatic (colour) and achromatic (luminosity) contrasts between the two spectra. Chromatic (ΔS) and achromatic (f_D) contrasts were calculated between the reflectance of the six bait treatments (R^{bait}), and the values of R^{cryptic} under the four environmental conditions. Values of ΔS and f_D were calculated using the software SPEC (Hadfield, 2004) that implements the species-specific visual model developed by Vorobyev and Osorio (1998). This model has been shown to accurately predict behavioural responses to colour contrasts for a range of taxa including birds, providing that spectral sensitivities and relative photoreceptor abundances are known (Vorobyev and Osorio, 1998; Vorobyev et al., 1998). Bait discriminability was calculated under conditions of 'natural daylight' (Endler, 1993). We based our calculations on the spectral sensitivities (S_i) and ocular media transmittance (O) of the wedge-tailed shearwater (*P. pacificus*, Hart and Vorobyev, 2005, Hart unpublished data).

Estimates of photoreceptor noise (e_i) required for these calculations were not available for the wedge-tailed shearwater. Instead, e_i was calculated using Eq. (10) from Vorobyev et al. (1998) for each receptor of the wedge-tailed shearwater using estimated values of e_i for the long wavelength sensitive cone of the Pekin Robin, *Leiostrix lutea* ($e_4 = 0.05$: Vorobyev et al., 1998) along with estimates of η_i for the wedge-tailed shearwater (Hart and Vorobyev, 2005). A similar approach was adopted

previously by Stuart-Fox et al. (2004, 2003). Theoretically, an object cannot be discriminated from its background if ΔS is less than or equal to the spectral 'discriminability threshold' (ΔS^t) of one (Vorobyev and Osorio, 1998).

Achromatic sensitivity is thought to be based on signals from retinal structures known as 'double cones'. Following Stuart-Fox et al. (2003) achromatic contrasts were calculated using f_D , where D represents the spectral sensitivities of the double cone. Achromatic sensitivity data for the double cones of wedge-tailed shearwaters were not available so f_D was calculated using sensitivity data from the chicken (*Gallus domesticus*). Because birds are thought to have highly conserved visual pigments this approach should provide a reasonable approximation (Stuart-Fox et al., 2003).

2.4. At-sea trials

To test if theoretical differences in discriminability between baits translated to differences in seabird behaviour, interactions with blue-dyed and non-dyed baits were documented during at-sea trials. These trials were conducted off the continental shelf near Wollongong, Australia between 34°24' and 34°31' E and 151°02' and 151°17' S. Trials were conducted from a 42ft charter vessel, the *Sandra K*. A total of seven days were spent at sea between the 8th of December 2005 and the 3rd of March 2006. To attract seabirds to the vessel we discharged fish scraps and fish oil but this was stopped prior to each longline or surface-presentation trial.

2.5. Longline sets

Each longline was set by deploying a 600-metre long 2.5 mm braided nylon line from the stern of the vessel at a rate of 1.5 m per second whilst steaming at three knots. This line was divided into ten sections by numbered buoys, with five baits in each section. Buoys were attached to the mainline with 2 m long buoy lines. Sections alternated blue-dyed and non-dyed baits and the colour of the first section was alternated between sets. Equal numbers ($n = 25$) of blue-dyed and non-dyed baits were presented during all sets. Only squid baits (weight = 250–320 g) were used and were attached to one metre long snoods (or branch lines) by threading a line through the mantle of the squid. No hooks were used in the trials. Snoods were weighted with a 38-gram swivel weight

Table 1 – Input parameters used to model ocean radiances and irradiances using the software Hydrolight

Hydrolight input components	Settings			
Inherent optical properties	Abcase 1; pure water			
Pure water absorption model	Pope and Fry (1997)			
Particle scattering phase function:	Petzold's average-particle			
Internal source and inelastic scatter	Chlorophyll fluorescence, CDOM and Raman			
Semi-empirical sky radiance model bottom boundary depth	Harrison and Coombes (1988) Radtran infinitely deep			
	Simulation number			
	1	2	3	4
Solar azimuth (degrees)	0	80	0	0
Cloud cover (%)	0	0	90	0
Chlorophyll concentration (mg/m ³)	0.02	0.02	0.02	0.5

and manually attached to the mainline with shark clips at ten metre intervals. The longline was left to soak for 5 min after deployment ceased, after which time hauling began. Baits were reused for all subsequent longline sets within one day.

During each set, all interactions between birds and the baited line were recorded, along with the species and the section number for each interaction. Interactions (from strongest to weakest) included: bait strikes, dives, alighting, looking at baits, and crossing the line (repeatedly crossing low over a particular section of the longline). When bird abundance was high, and thus a large number of interactions occurred, only alighting, dives and strikes were recorded. Behavioural data were continuously collected during deployment and the 5 min soak time. The same behavioural observer and data recorder was used for all sets.

2.6. Paired surface presentations

In each surface presentation, one dyed and one non-dyed bait were thrown simultaneously from the stern of the vessel whilst steaming at three to seven knots. Up to 180 presentations were conducted in each trial. Both fish and squid baits were used in paired presentations but within each trial only one bait type was offered in all presentations. Each squid was chopped into five equal sections, while fish were left whole. For each presentation we recorded if either bait was struck by a seabird, the species that struck the bait first, and the time (in seconds) to the first strike. Each paired presentation was observed for either 60 s or until both baits had received a strike. Presentations of dyed and non-dyed baits were alternated between the port and starboard side of the vessel.

2.7. Statistical analysis

Data from the longline sets were analysed using a generalised linear mixed model (GLMM), where the response variable was

the total number of behavioural interactions with each section type in each set. Potential explanatory variables included bait colour, bait colour of the first section, and an interaction term between these two variables. 'Day' was included as a random term in all models to control for variation in environmental conditions and bird abundance between days. All explanatory variables were included in the full model. Non-significant variables ($p > 0.05$) were then removed sequentially until only significant terms remained in the best fitting model. Longline data were analysed first using all observed interactions, and second using only landing, diving, and bait strikes.

For the paired surface presentations chi-squared analysis was used to determine if the response to dyed-bait differed to non-dyed bait. A logistic regression model examined if the response to blue-dyed bait differed relative to the number of days since the start of the study, bird abundance (total counts), and to the abundance of wedge-tailed and flesh-footed shearwaters (the two most abundant birds during the study). All variables were initially included in the model then non-significant terms were removed in a stepwise fashion until only significant terms remained.

3. Results

3.1. How cryptic are blue-dyed baits?

Results from simulation runs 1 and 4 alone (0.02 and 0.5 mg/m³; Table 2) are reported here because only chlorophyll concentration was found to alter greatly the values of R^{cryptic} .

Raw reflectance spectra showed that treating fish and squid with blue-dye changed the shape of their reflectance curves to more closely match the reflectance of the ocean at when both the bait and observer are at zero or 15 m depth (R^{cryptic} ; Fig. 1) regardless of ocean conditions (0.02 and 0.5 mg/m³ of chlorophyll; Fig. 1). The blue-dye changed the

Table 2 – Summary of generalised linear mixed modelling (GLMM) of seabird interactions with blue-dyed and non-dyed baits presented during longline trials

Variable	Wald χ^2 statistic	df	P
(a) Random term (day): estimate = 0.51; s.e. = 0.35.			
<i>Full model</i>			
Bait colour	43.4	1	<0.001
Colour of bait on 1 st section	0.01	1	0.9
Bait colour*Colour of bait on 1st section	1.4	1	0.2
<i>Best fitting model</i>			
Bait colour	44.8	1	<0.001
(b) Random term (day): estimate = 0.98; s.e. = 0.76.			
<i>Full model</i>			
Bait colour	17.3	1	<0.001
Colour of bait on 1st section	0.3	1	0.6
Bait colour*Colour of bait on 1st section	1.6	1	0.2
<i>Best fitting model</i>			
Bait colour	17.85	1	<0.001
Data sets for all interactions (a) and interactions of landing, driving and strikes only were analysed separately (b). Wald χ^2 statistics and associated P values are presented for each explanatory variable when fitted last in the full model. Day was included as a random term in each model.			

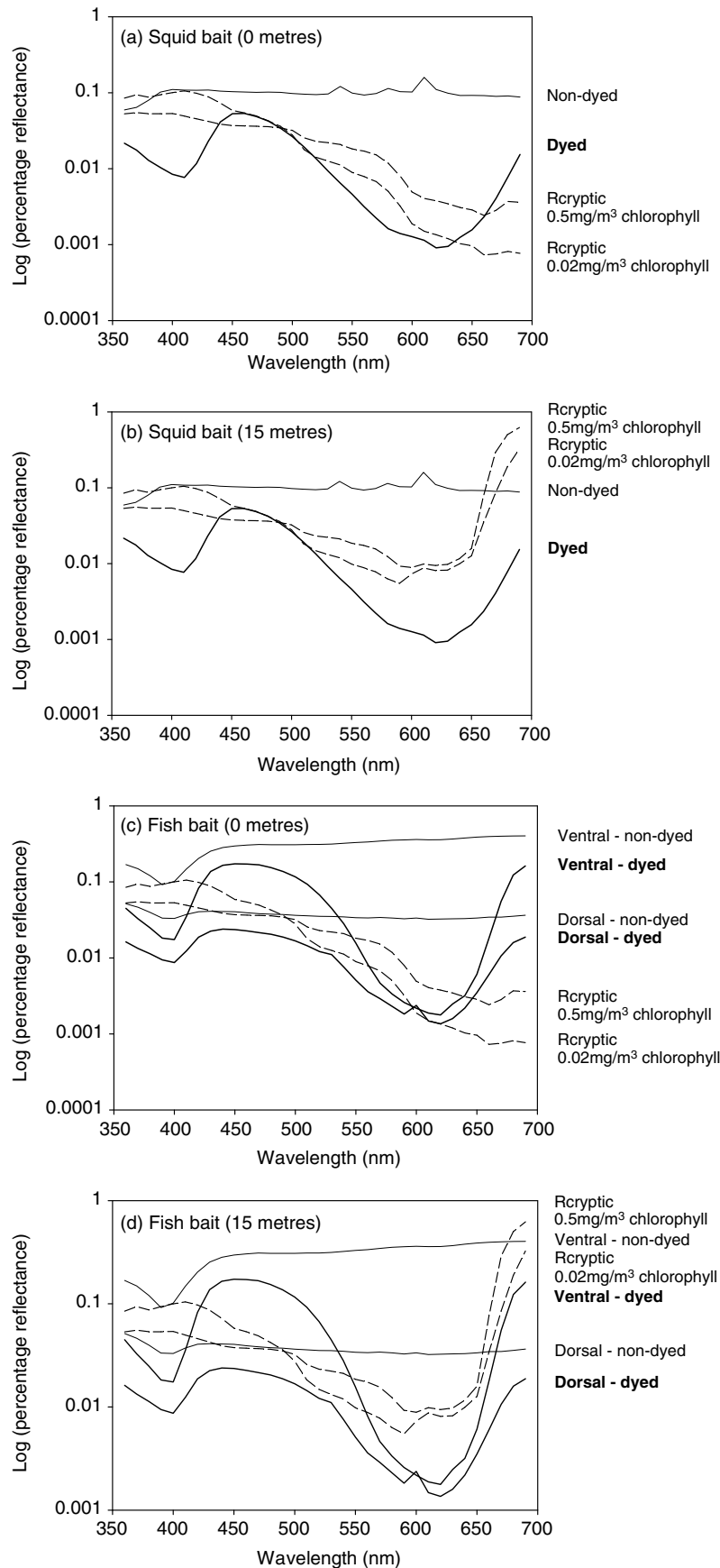


Fig. 1 – Raw reflectance spectra of non-dyed and 0.5% blue-dyed squid (a and b) and fish baits (c and d) plotted with the predicted reflectance spectra of the ocean at 0 or 15 m depth under the simulation conditions 1 (0.02 mg/m³ chlorophyll) and 4 (0.02 mg/m³ chlorophyll; Table 1).

hue (point of maximum reflectance) of the squid from a grey appearance (hue: 400–700 nm) to a dark blue colour (hue: 460 nm) with some high residual in the red part (650–700 nm) of the spectrum (Fig. 1a and b). The ventral and dorsal surfaces of the non-dyed fish appeared grey (hue: 450–700 nm) and deep blue (hue: <400 nm), respectively (Fig. 1c and d). Following blue-dye treatment the spectral response for both surfaces was lower (darker) with a broad blue peak between 420 and 520 nm and a residual in the red region (650–700 nm). The dyed squid was comparable in intensity with R^{cryptic} at the surface (Fig. 1a) across all the spectral range, while the dyed ventral surface of the fish was only comparable with R^{cryptic} at the surface (Fig. 1c) in a narrow region of the spectrum (~550–650 nm).

The chromatic contrast of blue-dyed baits relative to the background ocean was lower, and therefore more cryptic, in both water conditions (0.02 and 0.5 mg/m³ chlorophyll) than non-dyed baits (Fig. 2a and b). All blue-dyed bait treatments

had ΔS values approaching or less than the discriminability threshold of one (Vorobyev and Osorio, 1998). The non-dyed dorsal surface of the fish bait was also relatively cryptic with ΔS values of 1.57 and 0.75 for 0.02 and 0.5 mg/m³ of chlorophyll respectively. All other non-dyed baits had ΔS values which were above one. In addition, baits were consistently more cryptic when viewed in the 0.5 mg/m³ chlorophyll concentration than in 0.02 mg/m³ concentration. The dyed dorsal surface of the fish bait viewed in 0.5 mg/m³ of chlorophyll was the most cryptic with a ΔS value of 0.14.

The application of blue-dye also reduced the achromatic contrast of both the squid and the dorsal and ventral surfaces of the fish bait relative to the background ocean. (Fig. 2c and d). However, no bait had a luminosity which perfectly matched the ocean for either chlorophyll concentration making all baits conspicuous to some degree. Both the blue-dyed squid and the blue-dyed dorsal surface of the fish had negative luminosities, indicating they were duller than the ocean,

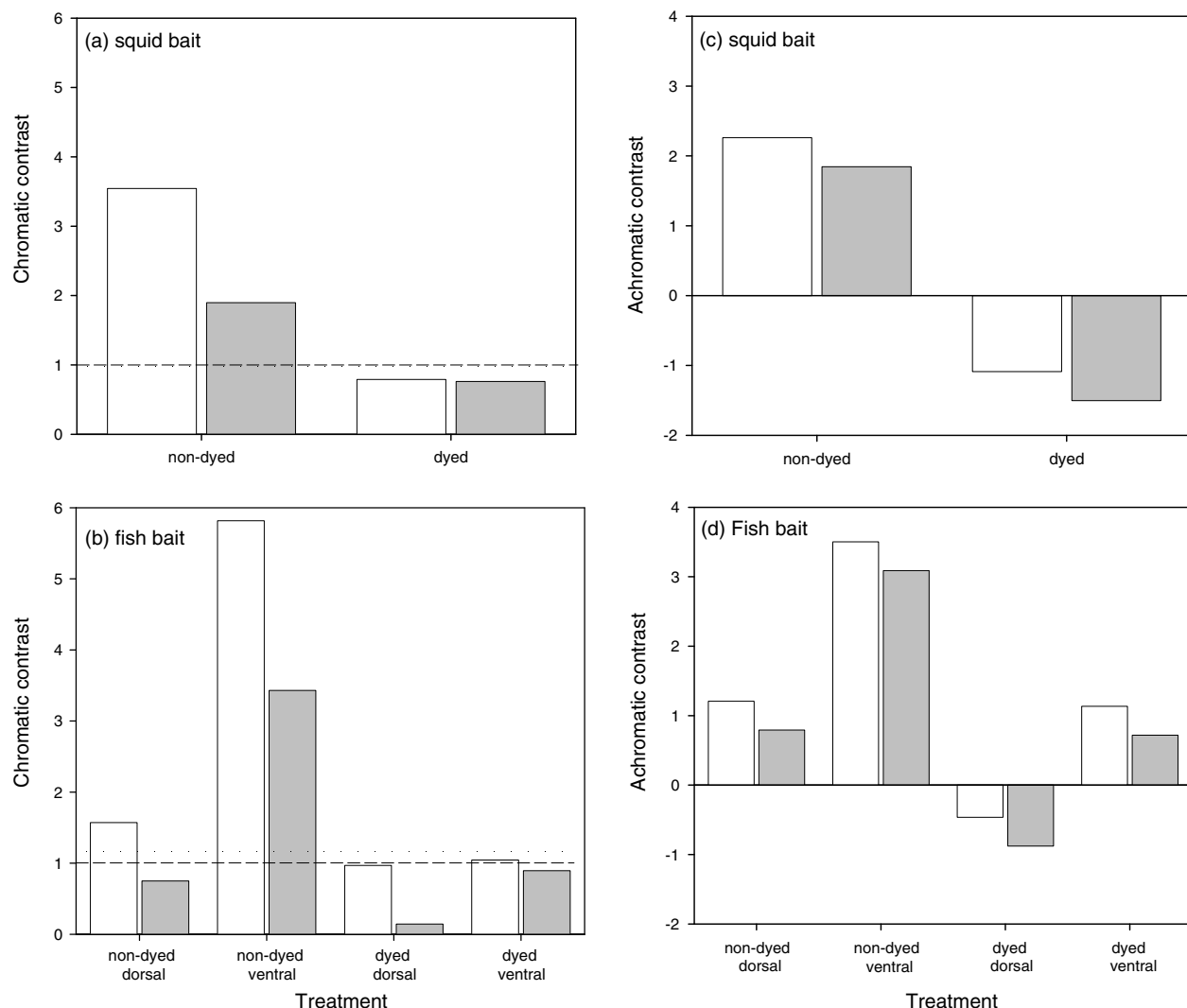


Fig. 2 – Chromatic (ΔS) (a and b) and achromatic contrast (f_D) (c and d) between fish and squid baits and a perfectly cryptic surface (R^{cryptic}) at 0 m depth (Johnsen, 2002). Contrasts between R^{cryptic} and baits are given for non-dyed and blue-dyed squid and fish against R^{cryptic} for Hydrolight simulations with 0.02 mg/m³ (open bars) and 0.05 mg/m³ of chlorophyll (grey bars) (Table 1). The dotted line indicates the theoretical discriminability threshold (Vorobyev and Osorio, 1998).

while the dyed ventral surface of the fish bait had a positive luminosity.

Vorobyev and Osorio's (1998) model predicted that all baits would be more apparent to seabird to some degree because no bait perfectly matched the ocean radiance in either chlorophyll concentration (R^{cryptic} for 0.02 and 0.5 g/m³; Fig. 1). However the blue-dyed squid was theoretically the most cryptic with low chromatic contrast and low achromatic contrast (Fig. 2). Conversely, the blue-dyed fish bait was likely to be more conspicuous to seabirds due to the strong achromatic contrast of the ventral surface.

3.2. Does blue-dyed bait reduce seabird interactions at sea?

A total of 29 species of seabirds were observed during trials, the majority of which were procellariiform seabirds. Generally wedge-tailed shearwaters dominated species composition (>65%), however on the final two days of trials similar numbers of flesh-footed and wedge-tailed shearwaters were present (spot count data available from authors).

A total of 1300 squid baits were deployed over 26 longline sets. A total of 1288 interactions were recorded. Significantly fewer interactions were observed in line sections with blue-dyed squid than in sections with non-dyed squid for all interactions (Table 2; Fig. 3). The same result was recovered when only the strongest interactions (alighting, diving and strikes) were considered (Table 2; Fig. 3). A mean of 37.7 (SE $\pm$ 5.4) interactions per set were recorded for non-dyed squid and 11.9 (SE $\pm$ 1.6) interactions per set were recorded for blue-dyed squid bait. When only landing, diving and strikes were considered, a mean of 12.4 (SE $\pm$ 2.4) interactions per set for non-dyed bait and 4.2 (SE $\pm$ 0.9) interactions per set for blue-dyed bait were recorded.

The colour of the baits in the first section of the line did not significantly affect the total number of interactions or the number of landings, dives and strikes within each bait treatment (Table 2). The predicted mean number of interactions, after controlling for 'Day' effects (GLMM), closely matched the mean number of interactions observed during this study (Fig. 3).

3.3. Surface presentations

When blue-dyed and non-dyed baits were presented in paired surface presentations significantly fewer blue-dyed baits were struck by seabirds than non-dyed baits (squid: $\chi^2 = 1215$, $df = 3$, $p < 0.0001$; fish: $\chi^2 = 54$, $df = 3$, $p < 0.0001$; Fig. 4). Within each trial day 75–98% of non-dyed squid baits presented were struck compared with only 3–8% of blue-dyed squid baits. The proportion of blue-dyed squid struck did not change significantly over the duration of the study ($\chi^2 = 2.4$; $df = 1$; $p = 0.12$). In contrast the proportion of blue-dyed fish baits struck increased significantly over the duration of the study from 47% on the first day of trial to between 87% and 90% over the last three days. On the final day of trials there was no significant difference in the rate of take between blue-dyed and non-dyed fish baits ($\chi^2 = 2.2$; $df = 3$; $p = 0.54$) but over all trials significantly fewer blue-

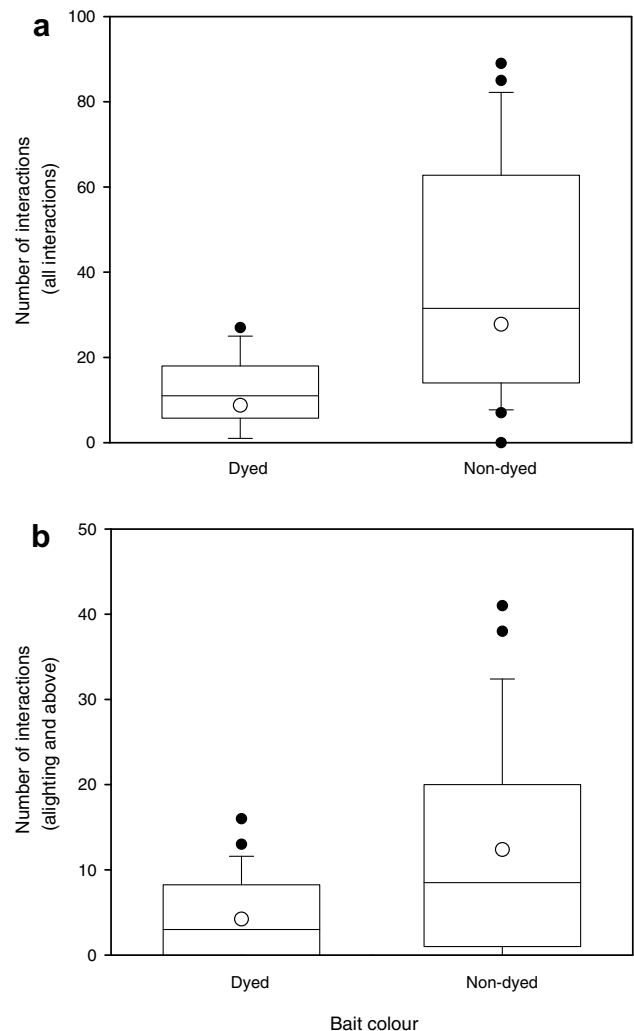


Fig. 3 – Total number of interactions per set (N = 26) relative to bait treatment for: (a) all interactions including looking, crossing the line, landing, diving and bait strikes; and, (b) strong indicators of landing, dives and bait strikes only. The middle line of boxes shows the median; filled circles represent outliers; and, open circles represent predicted means from a GLMM that controlled for 'day' effects (Table 2). Only squid baits were used in the longline-based trials.

dyed fish baits were struck than non-dyed fish baits ($\chi^2 = 3.4$, $df = 3$, $p < 0.0001$).

The proportion of blue-dyed fish baits struck on each day correlated with both the number of days since the start of the study ($\chi^2 = 27.8$; $df = 1$; $p < 0.001$) and the total bird abundance ($\chi^2 = 9.5$; $df = 1$; $p = 0.002$). Wedge-tailed and flesh-footed shearwater abundances did not affect the proportion of blue-dyed fish baits struck ($\chi^2 = 3.0$; $df = 1$; $p = 0.09$; and, $\chi^2 = 0.2$; $df = 1$; $p = 0.66$, respectively).

When both fish baits in a pair received strikes, the non-dyed bait was usually struck first (73%, $N = 75$; $\chi^2 = 16$; $df = 1$; $p < 0.001$). Strikes on both squid baits were rarely observed but when recorded bait treatment did not affect the outcome (non-dyed bait struck first = 52%, $N = 23$; $\chi^2 = 0.04$; $df = 1$; $p = 0.83$).

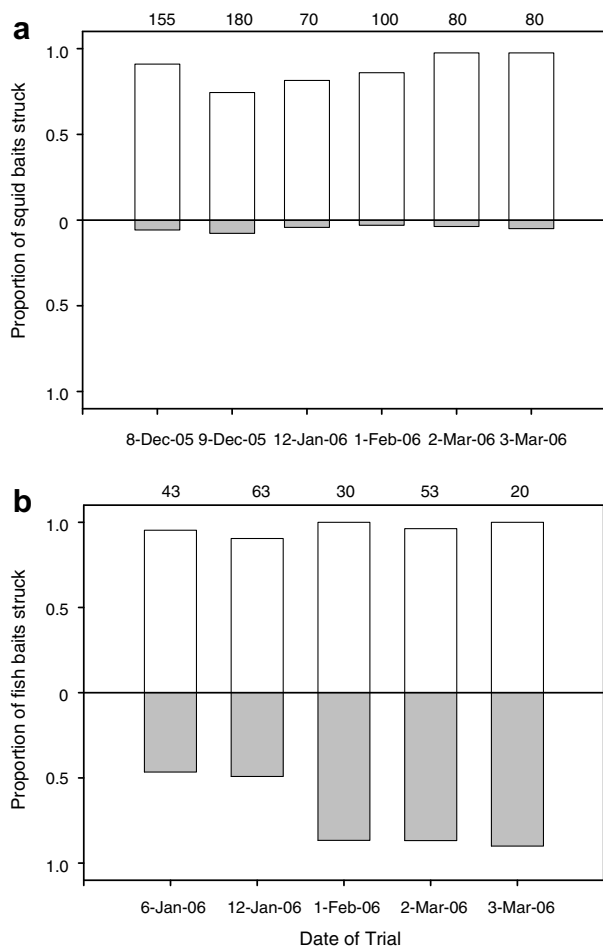


Fig. 4 – Proportion of (a) squid and (b) fish baits that received strikes from seabirds during each trial day (white bars – non-dyed bait; grey bars – blue-dyed bait). Baits were presented at the surface in pairs of dyed and non-dyed bait; the total number of pairs presented per day is given above each column.

4. Discussion

This is the first study to assess the spectral properties of blue-dyed baits and to quantify bait crypsis using the visual acuities of a procellariiform seabird. Our results demonstrated that applying blue-dye to both fish and squid baits decreases bait discriminability in terms of both chromatic and achromatic contrasts. Chromatic contrasts for all blue-dyed bait surfaces had ΔS values below 1.04 indicating that these baits are likely to be difficult for wedge-tailed shearwaters to discern from the background ocean in the specific sea depth and environmental conditions tested here (Table 2). The non-dyed dorsal surface of the fish bait, viewed in 0.02 mg/m^3 of chlorophyll was also relatively cryptic with a ΔS value of 0.75. In contrast, all other non-dyed bait surfaces had ΔS values above the discriminability threshold of one suggesting that all are likely to be relatively conspicuous to procellariiform seabirds. Non-dyed fish baits are particularly visible due to the high contrast of the ventral surface.

Relative achromatic contrasts indicate that no bait surface had a luminosity that perfectly matched the ocean for either chlorophyll concentration, suggesting all baits are conspicuous to wedge-tailed shearwaters in terms of brightness contrasts. However, unlike for chromatic contrasts, there is no recognised discriminability threshold for achromatic contrast; therefore it is not possible to predict if the achromatic contrast between blue-dyed baits and the ocean is detectable by seabirds.

Previous studies have shown that the crypsis of an object in the pelagic ocean environment is particularly dependent on viewing angle, but can also be affected by time of day, water type (e.g. chlorophyll content) and depth (Johnsen, 2002,2003; Johnsen and Sosik, 2003). For the specific set of environmental conditions examined in this study (Table 1), cloud cover and solar azimuth had a negligible effect on bait crypsis whereas increased chlorophyll concentrations consistently reduced the discriminability and contrast of both dyed and non-dyed baits under the generally low ('blue water') chlorophyll concentrations tested here (Fig. 2).

Depth also affected bait crypsis. Raw reflectance spectra suggested that blue-dyed baits would be less cryptic if viewed from zero distance at 15 m depth than if the bait was viewed at zero distance just below the ocean's surface (0 m). At 15 m blue-dyed baits do not reflect enough light above 600 nm (yellow/red) to closely match the ocean's colour. However, it is less likely that baits will initially be viewed at this depth; due to the energetic cost of diving the majority of procellariiform seabirds do not dive in search of food unless the prey is first visible from the water's surface (Prince et al., 1994; Prince, 1987; Shealer, 2002).

Three potentially important factors were not assessed here either due to the limitation of current visual modelling methods or simply to minimise the number of environmental variables included in this preliminary analysis. First, visual models assumed that the baits were viewed from directly above. However, it has been demonstrated that even if an object's is cryptic from above, it may be visible when viewed horizontally or from below (Johnsen, 2002,2003; Johnsen and Sosik, 2003). Consequently, seabirds using circular foraging strategies (Johnsen, 2002; Johnsen and Sosik, 2003; Prince, 1987) may reach a viewing angle which cause otherwise cryptic baits to become more visible against the ocean background. Further, if a bird dives and views a bait from below, the bait is likely to have high contrast against the background of bright sunlight (Johnsen, 2002,2003). This high contrast when viewed from below may, in part, explain why changes in catch rates of target fish species have not been reported when blue-dyed baits are used (Lydon and Starr, 2004; McNamara et al., 1999).

Second, it is difficult to adapt current light and visual models to account for the attenuation of the visual signal through the water, across the air–water interface, then through air back to the viewer's eye. Consequently, we assumed baits were being viewed by seabirds with their head submerged and viewing baits at zero distance. Certainly seabirds frequently search for food by landing and placing their heads underwater (Huyn and Prince, 1997; Shealer, 2002) so the data presented here provides realistic information on the ability of a seabird to discriminate a bait at close range. It seems likely

that baits viewed from greater distance and through the air–water interface will be less visible due to the deterioration of the visual signal with distance and due to strong reflectance at the water's surface.

Finally, the visual models here did not include reflectance data below 360 nm due to the limitations of the Hydrolight software. However, it is unlikely that the absence of data for this region of the visible spectrum will greatly affect our ability to determine the discriminability of baits by seabirds; wedge-tailed shearwaters are not particularly sensitive to light in the 300–360 nm range due to their UV cone peaking at 400 nm (Hart and Vorobyev, 2005), also light in the ultra-violet range is rapidly absorbed in water (Hastad et al., 2005).

The visual models predicted that dyed-baits would be less visible to foraging seabirds and this hypothesis was largely supported by at-sea trials. When blue-dyed and non-dyed squid were presented simultaneously on a longline, 68% fewer interactions were recorded within sections of the line that contained blue-dyed baits compared to sections with non-dyed baits (Fig. 3). These results support those of Boggs (2001) and McNamara et al. (1999), who recorded a 94% and 92% reduction in interactions with blue-dyed bait, respectively. Together these results demonstrate the potential of blue-dyed squid to effectively reduce interactions with longline gear compared to no mitigation measure.

Past studies have assumed that any observed reduction in interactions with blue-dyed baits is a result of bait crypsis, simply because dyed baits appear less apparent to the human eye. Results from our visual models suggested that the blue-dye does make squid less visible to seabirds and during sea trials there were consistently fewer interactions with the dyed squid baits throughout the duration of the study. In contrast, the visual models suggest the dyed fish baits are less cryptic than squid baits and certainly a higher proportion of blue-dyed fish bait were struck during the at-sea trials. Of course, an alternative explanation for the observed reduction in strikes is that the blue-dye elicits an aversion, neophobia or a combination of factors (Lyndon and Starr, 2004). An aversion may be triggered by blue-dyed baits having a superficial resemblance to poisonous blue bottles (Portuguese man-o-war; *Physalia utriculus*) or other dangerous or unpalatable species (similar principles to Batesian mimicry, see Dittrich et al., 1993; Lindstrom et al., 2001; Lindstrom et al., 1997), while neophobia acts as protection against potential attack and/or poisoning from ingesting toxic prey by slowing the incorporation of novel foods into the diet (Greenberg, 1990; Johnson, 2000; Jones, 1986; Marples and Kelly, 1999; Visalberghi et al., 1998).

If aversion or neophobia rather than crypsis is driving responses to blue-dyed fish bait, then birds may be more willing to sample blue-dyed baits during times of increased competition, food shortages or when feeding young (e.g. Greenberg, 1990; Marples and Kelly, 1999; Visalberghi et al., 1998). This may explain why a larger proportion of blue-dyed fish baits were struck during surface presentations compared with blue-dyed squid and why the birds increased their intake of blue-dyed fish as the study progressed.

A successful bycatch mitigation technique needs to be effective regardless of environmental conditions, seabird abundance or composition, or the extent of exposure to the

mitigation technique; these factors that are highly variable within areas where longline fishing occurs (Brothers et al., 1999; Gilman et al., 2003). Our results suggest that blue-dyed fish are unlikely to be effective as a long-term seabird bycatch mitigation technique because, in this study, the strike rate on blue-dyed fish baits increased over time. In contrast, over this three month study, blue-dyed squid baits caused a strong and consistent reduction in seabird interactions relative to non-dyed squid baits. However, it is not known whether blue-dyed squid will be equally effective in all conditions and remain effective with increased exposure, therefore its application within commercial longline fisheries would require monitoring.

Inevitably the employment of any bycatch mitigation technique is dependent on the willingness of fishers to adopt them (Brothers et al., 1999; Gilman et al., 2003; Hall et al., 2000). Although legislating for the mandatory deployment of mitigation techniques will increase their use, enforcement is costly and not always effective (Gilman et al., 2003; Gilman et al., 2005). Consequently, the successful mitigation techniques are likely to be those that fishers perceive to be safe, effective, economic, and which do not significantly alter their current fishing behaviour. Blue-dyed bait is certainly safe, relatively cheap (around \$US1 per 100 squid; Boggs, 2001), requires little capital investment and does not require any modifications to fishing gear, boats or operating behaviour. This is in marked contrast to other mitigation methods such as side-setting, weighted lines, setting chutes and bait pods. However, blue-dyed bait, if not supplied commercially, can be inconvenient to prepare and it stains clothing, skin and the vessel's decks (Gilman et al., 2003). Also the cost of blue-dyed baits is ongoing and may be perceived as an economic disincentive to fishers (Gilman et al., 2003). Finally, it will be necessary to provide convincing evidence that blue-dyed bait is an effective approach to reduce seabird interactions yet does not affect catch rates.

No mitigation technique has been shown to completely eliminate seabird bycatch, but blue-dyed bait may increase the effectiveness of other proven seabird bycatch mitigation techniques such as bird scaring lines or weighted lines. The use of multiple approaches has been championed in CCAMLR fisheries which, through the mandatory use of bird scaring lines together with line weighting, achieved a 99% reduction in seabird bycatch (Small, 2005). Blue-dyed bait has yet to be comprehensively tested with other techniques but recently Minami and Kiyota (2006) showed that using blue-dyed bait together with bird scaring lines was more effective at reducing seabird bycatch in a pelagic longline fishery than employing either technique alone.

Acknowledgements

This project was funded by the Natural Heritage Trust of the Department of Environment and Heritage. We thank Captain Carl Loves, Mick (Sandra K), Lindsay Smith, and Janice Jenkin-Smith (SOSSA) for their invaluable and expert assistance in experimental design, technical support logistics and fieldwork. Arnold Dekker of CSIRO Land and Water provided advice on modelling light in water. We also thank

the following people for their advice and encouragement: Barry Baker, Misha Vorobyev, Nathan Hart, Daniel Osorio, Martin Scott, John Garvey, Suze Baird, Vera Keala, and David Kreutz.

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