DRAFT MANUSCRIPT

The potential of blue-dyed bait to reduce seabird bycatch in pelagic longline fisheries

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Abstract

Blue-dyed bait is a seabird bycatch mitigation technique which is assumed to reduce the contrast between the bait and the ocean background making baits visually cryptic to seabirds. We tested this assumption in two ways. First, using measured spectral profiles of blue-dyed baits (fish and squid) and modelled spectral profiles of the ocean under set conditions, we assessed how cryptic baits may be to wedge-tailed shearwaters (*Puffinus pacificus*) based on the known visual characteristics of this species. Results showed that no baits were perfectly cryptic against the background ocean, but blue-dyed squid were relatively cryptic both in terms of chromatic and achromatic contrasts. However, data indicated blue-dyed fish bait were more apparent due to their ventral surface being brighter than the ocean. 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 three to eight percent of blue-dyed squid baits were struck over the duration of the study compared with 75% to 98 % of non-dyed squid bait. In contrast, approximately 48% of all blue-dyed fish 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 indicate blue-dyed *squid* bait may decrease seabird bycatch on commercial longline fishing vessels whereas blue-dyed *fish* bait did not significantly reduce seabird interactions over the entire duration of this study.

Keywords: Crypsis, blue-dyed bait, seabird bycatch mitigation, albatross.

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 have shown a link between a decline in some seabird populations and bycatch rates in nearby fisheries (Weimerskirch et al., 1997; Hall et al., 2000; Tuck et al., 2001). 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 (Gales et al., 1998; Baker et al., 2002). These birds strike at the baits, usually during line setting where they become hooked and then drown as the line sinks (Tuck et al., 2001; Baker et al., 2002; Gilman et al., 2005). In addition, large, aggressive species such as the wandering albatross may become hooked or tangled when taking baits from diving birds returning to the surface (Gales et al., 1998; Baker et al., 2002).

Catch rates of seabirds in longline fisheries are highly variable ranging from 0.023 to 5.03 birds per 1000 hooks and are thought to be dependent on environmental conditions including light levels, sea surface conditions, bird abundance, moon phase, and season (Lydon and Starr, 2005; Gomez Laich et al., 2006) as well as whether the longline 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;

Lokkeborg, 2003; Gilman et al., 2005; 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 inconvenient, dangerous, costly, or the long term economic benefits are not immediately apparent (Hall et al., 2000; Gilman et al., 2003; Minami and Kiyota, 2004b; Minami and Kiyota).

Blue-dyed bait is a seabird bycatch mitigation technique that has been used in the Hawaiian, Brazilian and Japanese pelagic longline fleets (McNamara et al., 1999; Baird, 2001; Minami and Kiyota, 2001; Gilman et al., 2003). It is assumed that the blue-dyed 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 (McNamara et al., 1999; Boggs, 2001; Minami and Kiyota, 2001; Gilman et al., 2003; Minami and Kiyota, 2004a; Lydon and Starr, 2005; Minami and Kiyota, 2006).

To date, no studies have examined the spectral properties of blue-dyed baits or quantified how seabirds might perceive blue-dyed baits using their specific visual acuities rather than relying on the human visual system (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 can be discriminated in the ocean using species-specific visual models (Vorobyev and Osorio, 1998). By combining visual models with at-sea trials, this study aimed to: (1) determine blue-dyed fish and squid baits are theoretical less apparent

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to seabirds; and (2) whether dying baits blue can significantly reduce bait-strikes during at-sea trials.

Methods

To determine the relative discriminability of non-dyed and dyed baits, the reflectance spectra of the baits (R^{bait}) were determined and compared to the reflectance spectrum of the ocean ($R^{cryptic}$) using a species-specific visual model for the wedge-tailed shearwater (*Puffinus pacificus*).

Bait reflectance (R^{bait})

Blue-dyed baits were prepared by completely thawing squid (*Notodarus photololigo*) or fish (*Sardinops neopilchardus*) and soaking them in a 0.5% aqueous salt water solution of Brilliant blue food dye (C.I. 42090, E133, Australian Food Ingredient Suppliers) for 20 minutes. 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 degree 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 (*Notodarus photololigo*), ten readings were taken from the mantle and ten from the head. For fish baits (*Sardinops neopilchardus*), ten readings were taken from the dorsal surface and ten from the ventral surface. Five of the ten readings were taken with the probe facing towards the tail of the fish (downscale) and five facing towards the head (upscale). The spectrophotometer was recalibrated between each individual. The data were pooled and averaged across all individuals within each of the treatments in order to obtain one

indicative spectrum for each treatment type (non-dyed and blue-dyed for squid and non-dyed and blue-dyed for both the dorsal and ventral surfaces of the fish).

Calculating background ocean reflectance

For a bait to be cryptic, its reflectance spectra must have zero inherent contrast to the ocean background after accounting for the visual acuities of the observer. Such a reflectance spectra ($R^{cryptic}$) can be calculated using Equation 1 (corresponding to equation 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.

$$R^{cryptic}(\lambda) = \frac{\pi L_b(\lambda)}{E(\lambda)},$$
(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 environmental conditions (Mobley et al., 1993; Johnsen, 2002). This program requires the following input: depth of measurement, solar elevation and azimuth angle, atmospheric conditions, sea conditions, chlorophyll content and chlorophyll inflorescence 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 zero (just below the sea's surface) and 15 metres 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).

Visual modelling

The estimate the ability of a seabird to discern a bait with reflectance (R^{bait}) object it's the ocean background ($R^{cyrptic}$) 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 $R^{cyrptic}$ under the four environmental conditions. Values of ΔS and f_D were calculated using the software SPEC (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). We based our calculations on the spectral sensitivities (S_i) and ocular media transmittance (O) of the wedge-tailed shearwater (*Puffinus pacificus*, Hart and Vorobyev, 2005, Hart upublished data) and because visual pigments are highly conserved among related bird species (Hart, 2001), we assumed the results from our discriminability model would provide information relevant to other procellariiform species. Bait discriminability was calculated under conditions of 'natural daylight' (Endler, 1993).

Estimates of photoreceptor noise (e_i) required for these calculations were not available for the wedge-tailed shearwater. Instead , e_i was calculated using equation 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, *Leiothrix 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. (2003; 2004).

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/e_D, where D represents the spectral sensitivities of the double cone. The value of e_D is the same for all targets hence relative achromatic contrasts can be represented simply by the visual signal from the double cone (f_D). f_D was calculated using sensitivity data from the chicken (*Gallus domesticus*). Data from the wedge-tailed shearwater values were not available but as birds are highly conserved in their visual pigments this approach should provide a reasonable approximation for the achromatic sensitivity of wedge-tailed shearwaters (Stuart-Fox et al., 2003).

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. Prior to both longline and surface presentation trials, a burley trail was laid to attract seabirds, but was ceased prior to any bait presentations.

Longline sets

Longline were set by deploying a 600-metre long 2.5mm nylon line from the stern of the vessel at a rate of 1.5 metres 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 two metre 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 = 250-320g) 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 and manually attached to the mainline with shark clips at ten metre intervals. The longline was left to soak for five minutes 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, landing, crossing the line (repeatedly crossing the line over a particular section) and looking at baits. When bird abundance was high, and thus a large number of interactions occurred, only landing, dives and strikes were recorded. Behavioural data were continuously collected during deployment and the five minute soak time. The same behavioural observer and data recorder was used for all sets.

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 seconds 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.

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 (*Puffinus carneipes*) 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.

Results

How cryptic are blue-dyed baits?

Of the four sets environmental condition modelled in this study (Table 2) only chlorophyll

greatly altered $R^{cryptic}$ so we have only reported data from simulation runs 1 and 4 here.

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 metres depth ($R^{cryptic}$; Fig 1.) regardless of ocean conditions

(0.02 and 0.5mg/m^3 of chlorophyll; Fig. 1).

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 0.5mg/m^3 chlorophyll) than non-

dyed baits (Fig. 2a). 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 fish was also relatively cryptic with ΔS values of 1.57 and 0.75 for 0.02 and 0.5mg/m^3 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 0.5mg/m^3 chlorophyll

concentration than in 0.02mg/m^3 concentration. The dyed dorsal side of the fish bait viewed

in 0.5mg/m^3 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. 2b).

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 side of the fish had negative luminosities, indicating they were duller than the ocean, while the dyed ventral side 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 0.5g/m^3; Fig. 1). However the blue-dyed squid was theoretically the most cryptic with low chromatic contrast and low achromatic contrast (Fig. 2a & b). Conversely, the fish bait was likely to be more conspicuous to seabirds due to the strong achromatic contrast of the ventral surface.

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 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 baits than in sections with non-dyed baits for all interactions (Table 2; Fig. 3), and when only landing, diving and strikes were considered (Table 2; Fig. 3). A mean of 37.7 (SE ± 5.4) interactions per set were recorded for non-dyed bait and 11.9 (SE ± 1.6) interactions per set were recorded for blue-dyed bait. When only landing, diving and strikes were considered, a mean of 12.4 (SE ± 2.4) interactions per set for non-dyed bait and 4.2 (SE ± 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).

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: χ^2=1215, df=3, p<0.0001; fish: χ^2=54, df=3, p<0.0001; Fig. 4). Within each trial day 75 to 98% of non-dyed squid baits presented were struck compared with only three to eight % of blue-dyed squid baits. The proportion of blue-dyed squid struck did not change significantly over the duration of the study (χ^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 to 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 (χ^2=2.2; df=3; p=0.54) but overall all trials significantly fewer blue-dyed fish baits were struck than non-dyed fish baits (χ^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 (χ^2=27.8; df=1; p<0.001) and the total bird abundance (χ^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 (χ^2=3.0; df=1; p=0.09; and, χ^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; χ^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; χ^2=0.04; df=1; p=0.83).

Discussion

This is the first study to assess the spectral properties of blue-dyed baits and 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 0.02mg/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 metres depth than if the bait was viewed at zero distance just below the ocean's surface (zero metres). At 15 metres blue-dyed baits do not reflect enough light above 600nm (yellow/red) to closely match the ocean's colour. However, it is less likely that baits will initially be viewed at this depth; in these conditions due to the high energetic cost of diving the majority of procellariiform seabirds do not dive in search of food unless the prey is first visible from above water (Prince, 1987; Prince et al., 1994; 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 have 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 (Prince, 1987; Johnsen, 2002; Johnsen and Sosik, 2003) 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 catch rates of target fish species have not been reported when blue-dyed baits are used (McNamara et al., 1999; Lydon and Starr, 2005).

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 (Huin 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 not particularly sensitive to light in the 300 to 360nm 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 McNamera 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. Combined results from visual models and at-sea trials indicate that blue-dyed squid may be at least partially cryptic to seabirds, as few interactions with baits occurred and there was no change in the number of interactions over the duration of the study. However, the results of the visual models, and the higher proportion of blue-dyed fish bait that were struck during at-sea trials suggest that blue-dyed fish baits are not perfectly cryptic. Instead, reactions to blue-dyed fish, and possibly blue-dyed squid may be caused by an aversion, neophobia or a combination of factors (Lyndon and Starr, 2003). 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., 1997; Lindstrom et al., 2001), 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 (Jones, 1986; Greenberg, 1990; Visalberghi et al., 1998; Marples and Kelly, 1999; Johnson, 2000).

If aversion or neophobia are driving responses to blue-dyed fish bait, rather than crypsis, the birds may be more willing to sample blue-dyed baits during times of increased competition or food shortages (e.g. Greenberg, 1990; Visalberghi et al., 1998; Marples and Kelly, 1999). 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 know 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; Hall et al., 2000; Gilman et al., 2003). 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 may be difficult to provide convincing evidence that blue-dyed bait is an effective approach to reduce seabird interactions while not affecting fish catches.

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 not been comprehensively tested with other techniques but Minami and Kiyota (2006) showed that using blue-dyed bait together with bird scaring lines was more effective at reducing seabird bycatch than employing either technique alone.

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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:	Petzgold's average-particle			
internal source and inelastic scatter	chlorophyll fluorescence, CDOM and Raman			
semi-empirical sky radiance model	Harrison and Coombes (1988) Radtran			
bottom boundary depth	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

Table 2. Summary of generalised linear mixed modelling (GLMM) of seabird interactions with blue-dyed and non-dyed baits presented during longline trials. Data sets for all interactions (Table 3.2a) and interactions of landing, driving and strikes only were analysed separately (Table 3.2.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.

(a) Random term (day): estimate = 0.51; s.e. = 0.35.

Variable	Wald χ^2 statistic	df	P
Full model			
Bait colour	43.4	1	<0.001
Colour of bait on 1st section	0.01	1	0.9
Bait colour*Colour of bait on 1st section	1.4	1	0.2
Best fitting model			
Bait colour	44.8	1	<0.001

(b) Random term (day): estimate = 0.98; s.e. = 0.76.

Variable	Wald χ^2 statistic	df	P
Full model			
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
Best fitting model			
Bait colour	17.85	1	<0.001

(a) Squid (0 m)

non-dyed

dyed

0.5mg chl

0.02mg chl

(b) Squid (15 m)

0.5mgchl

0.02mg chl

non-dyed

dyed

Wavelength (nm)
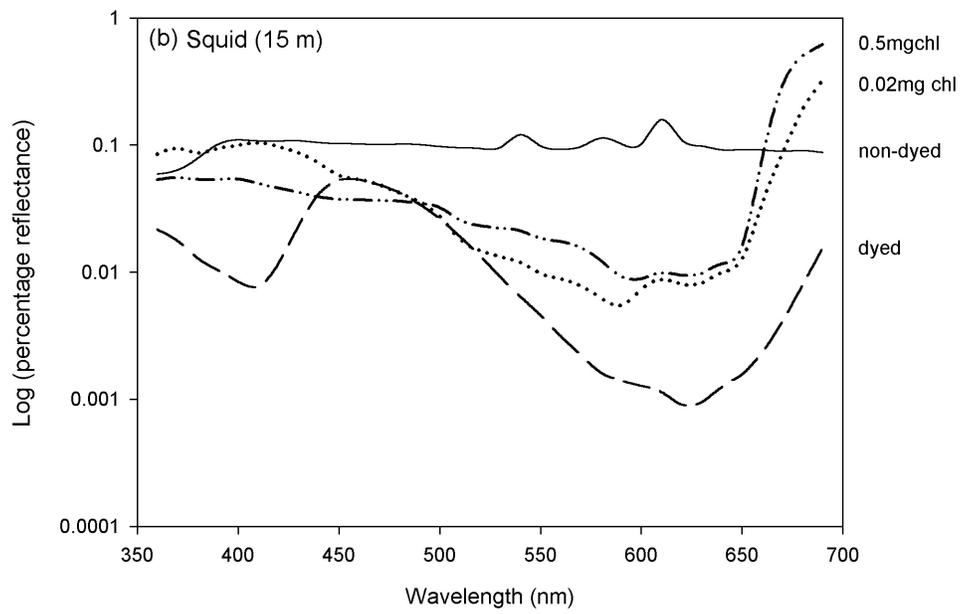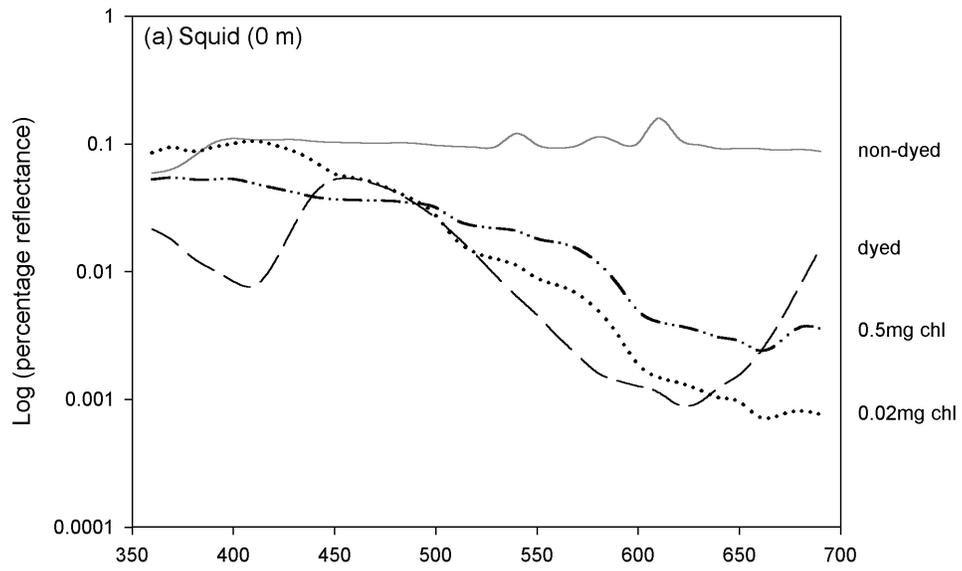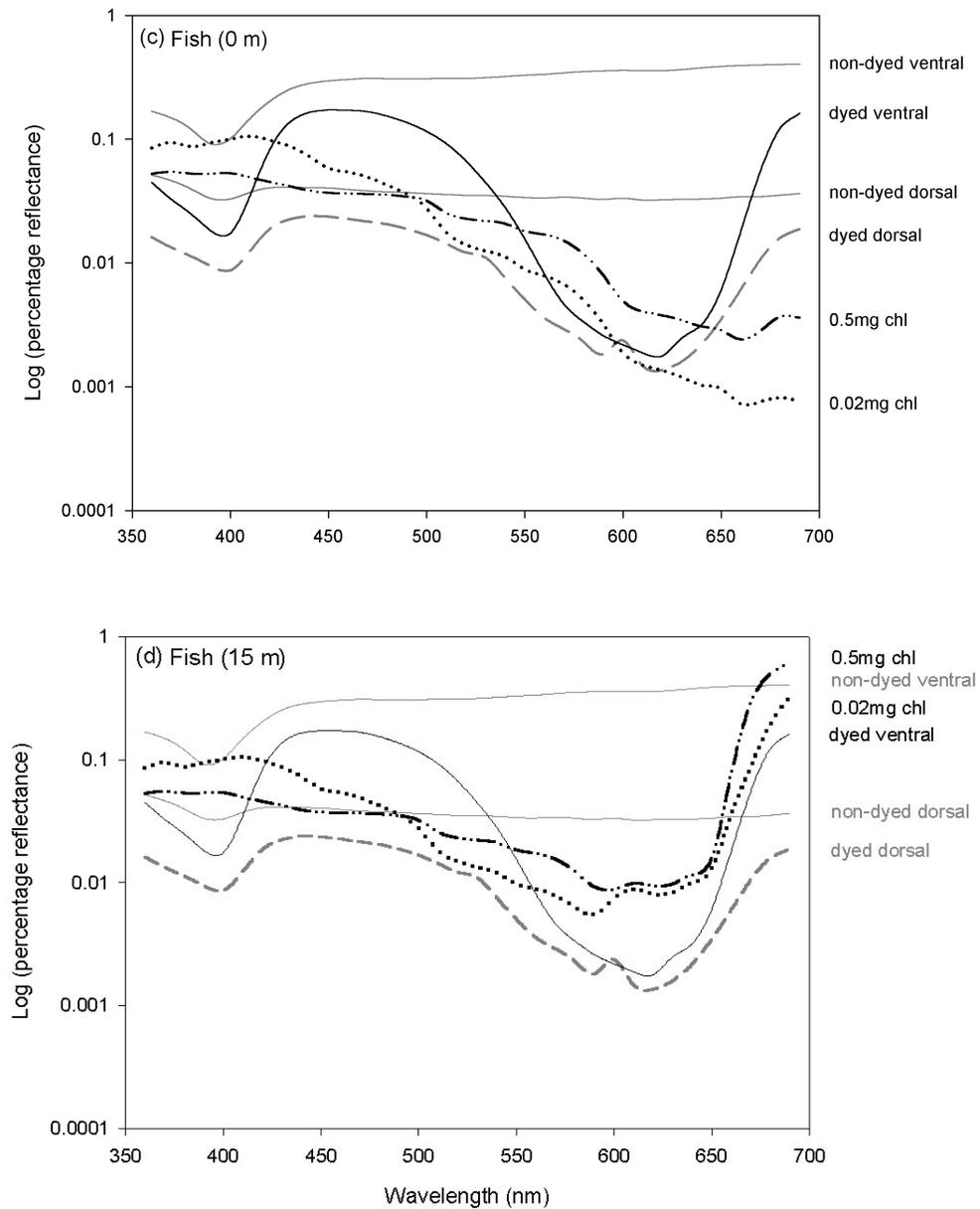
Figure 1. a) & b) Raw reflectance spectra of non-dyed and 0.5% blue-dyed squid (a & b) and fish baits (c & d) plotted with the predicted reflectance spectra of the ocean at 0 or 15 metres depth under the simulation conditions 1 (0.02 mg/m^3 chlorophyll) and 4 (0.02mg/m^3 chlorophyll; Table 2).

a)
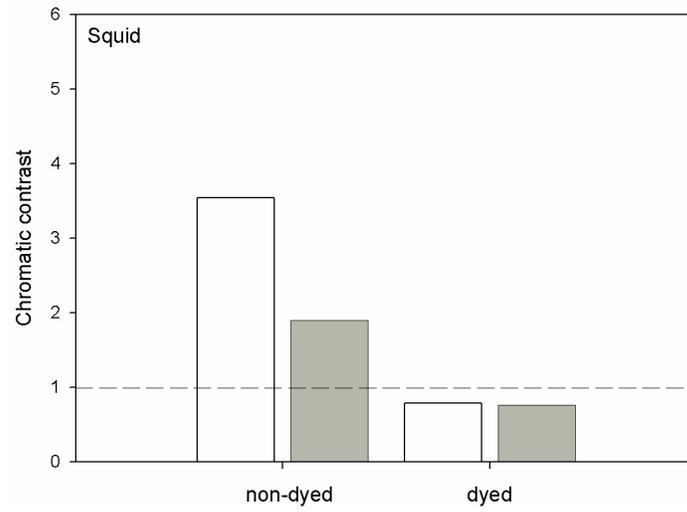
b)
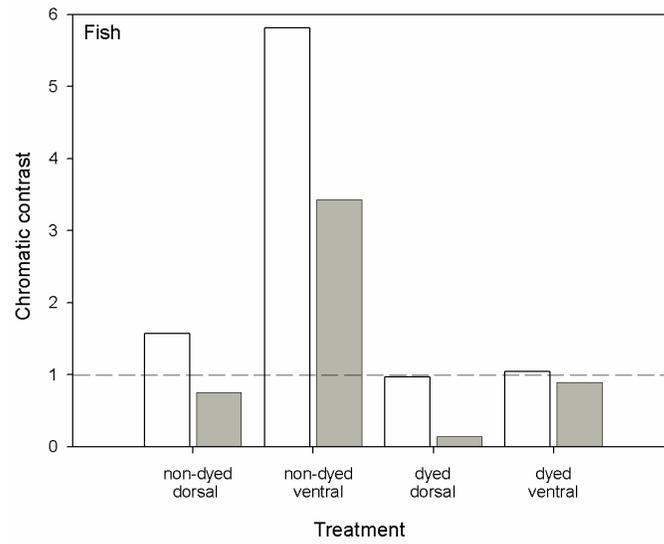
c)
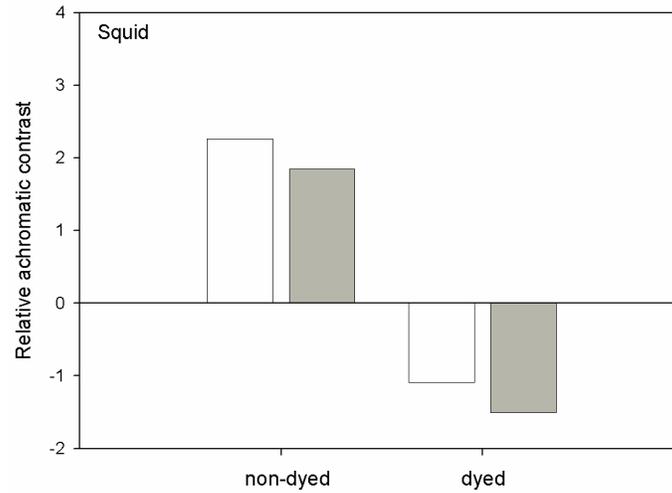
d)
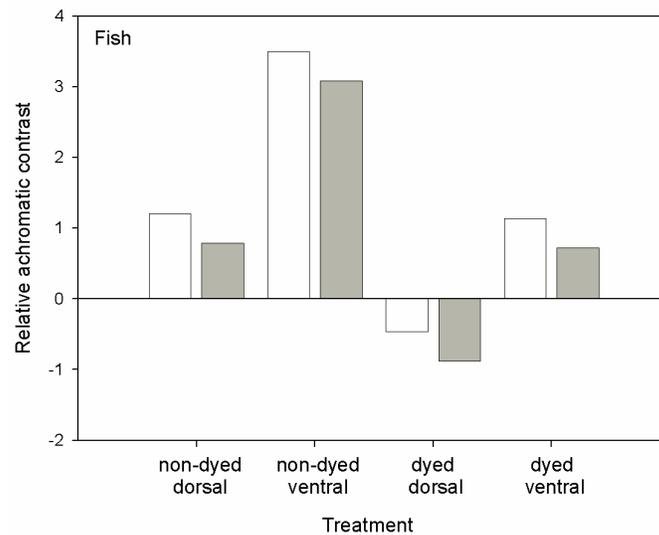
Figure 2. Chromatic (ΔS) (a & b) and achromatic contrast (f_D) (c & d) between fish and squid baits and a perfectly cryptic surface ($R^{crytpic}$) at 0 metres depth (Johnsen 2002). Contrasts between $R^{cryptic}$ and baits are given for non-dyed and 0.5% blue-dyed squid and fish against $R^{cryptic}$ for Hydrolight simulations with 0.02 (open bars) and 0.05mg/m^3 of chlorophyll (grey bars) (Table 1). Dotted line indicates the discriminability threshold, below which contrasts are increasingly difficult to discern (Vorobyev and Osorio, 1998). Achromatic contrast calculations used the double cone sensitivities of the chicken (Hadfield, 2004).

(a)

(b)
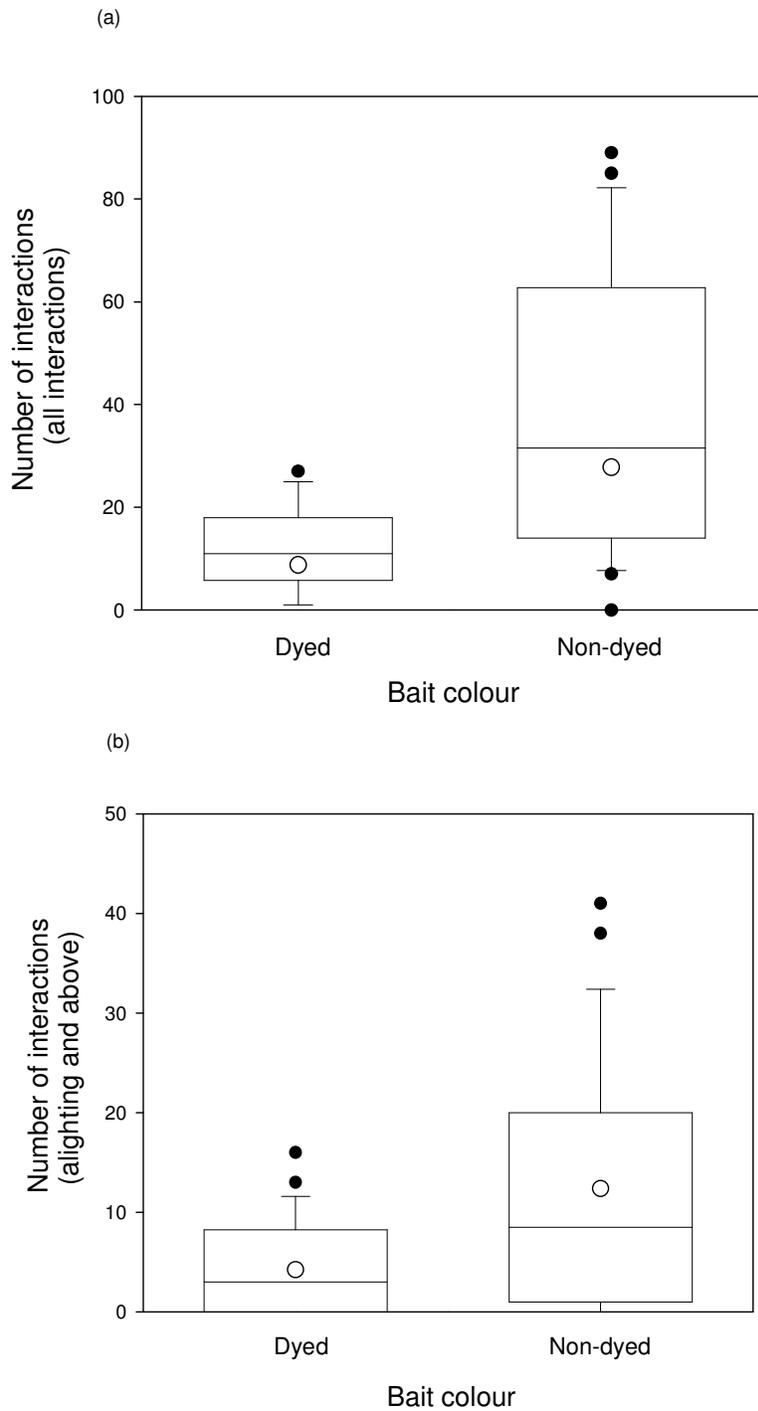
Figure 3. Total number of interactions per set (N=26) relative to bait treatment for: (a) all interactions including looking, crossing the line, landing, diving and bait strikes; and, (b) strong indicators of landing, dives and bait strikes only. The middle line of boxes shows the median; filled circles represent outliers; and, open circles represent predicted means from a GLMM that controlled for 'day' effects (Table 2).
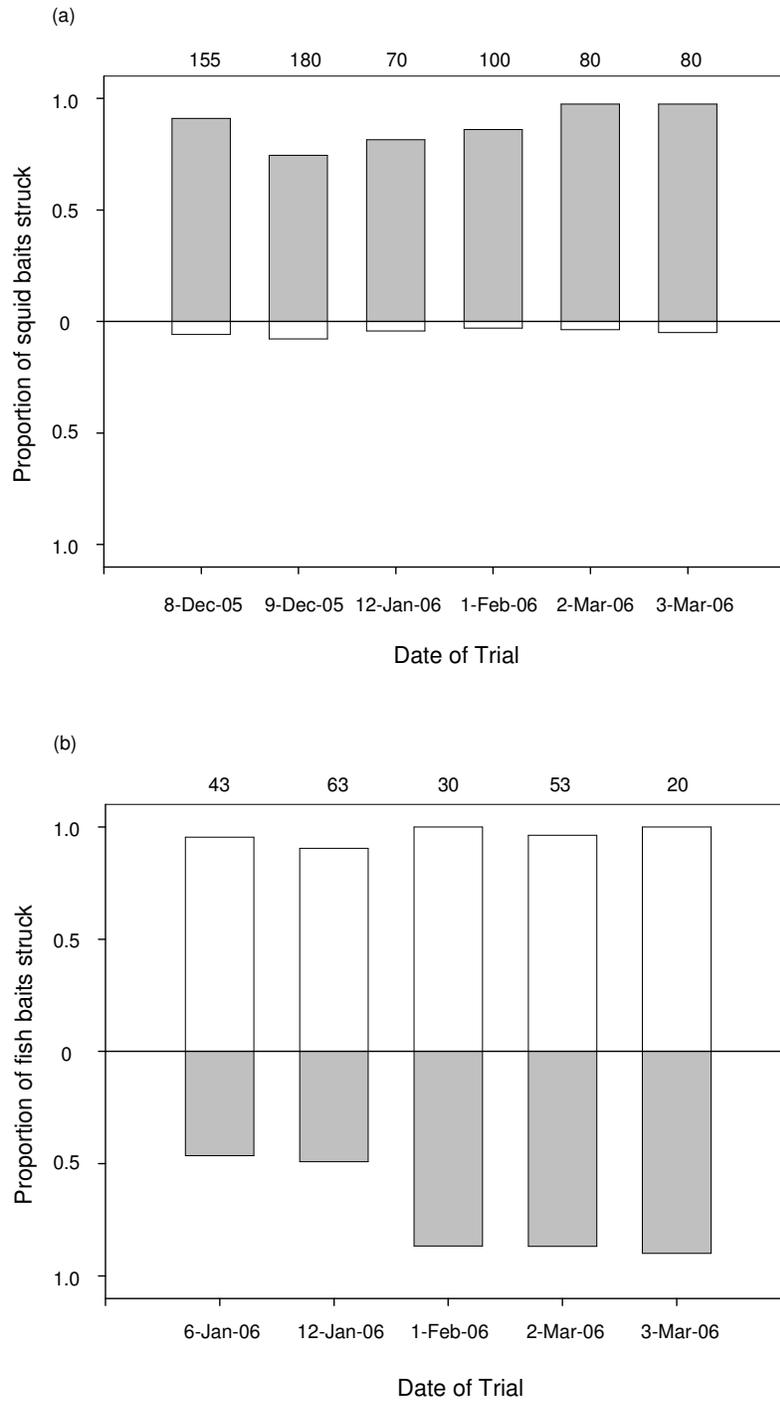
Figure 4. Proportion of (a) squid and (b) fish baits that received strikes from seabirds during each trial day (white bars - non-dyed bait; grey bars - blue-dyed bait). Baits were presented in pairs of dyed and non-dyed bait; the total number of pairs presented per day is given above each column.