"A Preliminary comparative study of netting colour upon the efficiency of gill nets, by catch, diver observations and photographic techniques"

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ABSTRACT

The efficiency of gill nets is almost certainly influenced by net visibility, and this is dependent upon its colour, brightness, the prevalent water type, ambient light levels and depth fished.

From previous work it has been found that the optimum colour/shade varies from area to area, with water type etc. and even between species sought after. The different approaches used have included trial fishing, diver observations and photography. These have been conducted both in situ in seas and lakes and in tanks and even swimming pools. The results from these are varied although, in general, lighter colours have been shown to be best in turbid waters. Furthermore, no previous work has attempted to draw any comparison between the 3 different approaches.

In this preliminary study 8 nets have been used; white (undyed), blue, yellow, green, red, grey, black and brown. Apart from comparative fishing in the Plymouth Sound area in various water types at 14 and 30m depths, some additional trials were conducted with the same nets surface rigged in Christchurch Bay, Dorset. For comparison both diver and photographic observations were also conducted in the Plymouth area.

With a few exceptions the 3 techniques appear to give comparable results in each water type and depth, although the data obtained for analysis were not extensive. Much useful experience was gained in the type of underwater experimental work that is essential in any realistic, in situ study of fishing gear. It is likely that the colour of fishing nets and the behaviour of fish that encounter them will be the theme of continued research within the Department of Marine Science and so a number of recommendations have been made for future workers in this field.

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Introduction

Gill and tangle net fishermen in different countries, sea areas, ports, on different grounds and at different times of the year tend to have different net colour preferences.

The most popular colour of salmon gill nets in north east England and Scotland are blue or grey, whereas in Ireland it is dark brown or green. In the cod fisheries of south west and west Iceland in depths of 10-90 fathoms (18.5-165 m) blue-grey netting; off the Norwegian coast in depths of 100-150 fathoms (185-275 m) they use grey-green nets and around English coasts green is used on the east coast and brown in the Moray Firth. (Burgess, 1971).

Popular colours used by fishery researchers in Scandinavia tend to be mainly red, brown, grey and rainbow coloured nets. The latter is felt to be the most effective, especially in daylight fishing on most fishing grounds. (Dr. Klemetsen, personal communication)*

In general the most commonly used colour tends to be green. This is reflected in the recent change of policy of one of England's leading net manufacturers; Bridport Gundry, who now stock green rather than the previously produced pristine white nets. This changing of preference was found throughout England and Ireland with manufacturers inability to supply suitable white netting for this project. Eventually Morep Limited were able to oblige.

Also brown still retains popularity; possibly from the days when all nets were brown due to the cutching treatment necessary for the natural fibre nets, that preceded synthetics, e.g. nylon.

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It is widely accepted as being advantageous to use nets correctly coloured to reduce their visibility, and that this is just as effective as rigging, in influencing the overall fishing efficiency of nets. (Baronov, 1924; Von Brandt, 1972; Burgess, 1971, 1980; Inoue et al, 1958; Kanda et al, 1958; Koike, 1958; Koike et al, 1958). However there still remains some schools of thought that feel that colouring gives no advantages and claim that uncoloured (white) nets fish equally well. Others restrict this claim to fishing at night and in deep water only, where any advantage of colouration would be less significant (Burgess, 1980; Nomura, 1957). Some claim advantages of colour both by day and night, although the optimum colour changes with illumination and depth (Hemmings & Lythgoe, 1965).

With use pristine white nets rapidly become grey-green or grey-brown with dye from the water, weed, mud etc. which is inherent with use, especially in a coastal fishery. But I feel that a correctly coloured net will be significantly better than an uncoloured net, although both will tend to undergo some discolour and lose their original brightness with use.

Factors that do have a more widely accepted influence on fishing efficiency are the characteristics of the net itself; these include mesh size, hanging ratio (E), twine thickness, softness, stiffness and extensibility, general rigging and setting, e.g. buoyancy, weighting, slackness of mounting twine, bridle length, tides etc. Manipulation of some of these factors including twine stiffness, extensibility and abrasion resistance as is required in ray nets and drift nets for soft fleshed species, e.g. herring, often incurs inherent brownish-black colouration from the post manufacture treatment with bitumen or some similar substance.

With such a wide range in colour preferences and demands from the fishing industry, net manufacturers and retailers are presented with a problem as to what colours and shades of netting to produce and stock in order to satisfy the demands of the consumer. Furthermore, there remains the possibility of fishermen using a sub optimum colour through ignorance of his requirements or being influenced by what the retailer has to offer.

With this background to the industry I feel there remains the requirement for a wide range of detailed research in this field. The main variables involved in deciding upon an optimal netting colour include:

- the interaction between brightness and saturation of colour of both the water and netting.
- the propagation of light through the water column described by the attenuation coefficients c and k.
- the available surface illumination that penetrates the surface.
- the effects of wavelength upon light penetration and depth fished.
- the type of substate if applicable,

and perhaps most importantly a better understanding of fish vision, i.e. what each fish species sees and how closely this correlates with vision in man. Also it is assumed that a fish is caught if it does not see or pay attention to the net.

There are an immense number of colours available; Oswald's Colour Atlas lists over 2,500 colours (Baranov, 1924), and if an optimum colour is ascertained for a particular species of fish, fishing ground, water mass and depth, then this remains optimal only as long as the water mass properties do not change and there are no adverse influences from other factors such as change in ambient light from direct to diffused as for an overcast day.

Due to the sheer size of the problem that this poses I can only hope to cast light upon a small aspect of this field. To this end a comparative study was carried out of the success of fishing with various coloured nets. Due to the range of colours possible it was difficult to decide upon what colours and shades to use. So using 7 standard "Dylon" synthetic dyes (see Burgess, 1980), 8 net panels of 3 inch (75 mm) mesh 210d/6 (R.140 Tex) white nylon were dyed in accordance with the dyeing instruction. The names designating the colours of the dyes used were Elephant Grey 21, Havana brown 5, Scarlet 32, Golden Glow 2, Ebony Black 8, Emerald 25 and Madonna blue 18. In future these net colours will be termed grey, brown, red, yellow, black, green, blue and white (undyed).

The nets were all identically constructed and fished in a fleet, each net being separated by about 2 metres to reduce any influence of one net upon another. The nets were fished either by day or by night, and usually bottom set in the Plymouth area; although original settings were surface set with the headlineabout 1 metre below the surface, due to the problems of weed drifting along the bottom, that is encountered in Christchurch Bay, Dorset, for most of the year.

For each setting recorded was:

- the number of fish in each colour net,
- the number per species of fish in each net,
- the totals per species,
- the number of fish caught overall,
- the hours fished,
- the approximate depth of water,
- the Secchi disc depth (D)
- the sea state (calm/rough)

- the wind direction and force (Beaufort scale),
- the cloud cover (overcast/cloudy/clear),
- the percentage beam transmittance at net depth (thus allowing determination of c and k from Secchi disc depth), and
- the nature of sea bed, if applicable.

It was also intended to measure surface irradiance per hour fished so that a quantitative analysis of irradiance at net depth could be made. But this proved impossible due to equipment failure.

As fishing was carried out either during the day or overnight (set at dusk and hauled at first light) it may be assumed that as catches were not intensive, catchability was not influenced significantly by previously caught fish in the net (see Kennedy, 1951). An important factor with night fishing is that due to exciting phosphorescence in the sea water the nets at night become more visible than over the twilight periods when the higher ambient light levels make the phosphorescence less conspicuous (Hemmings, 1965).

In the enhancment of these results diving observations were conducted upon the nets when fishing. For the prevailing conditions human visual ranges were measured for each net against a water background. This gave a range of relative brightness for the nets in situ, and assuming that fishes' vision is comparable with that of man, these should correlate with catches in each net. Secondly, each net was photographed whilst fishing at a standard range with available light. This gave a record of colour contrast between net and the water background as well as showing the relative contrasts in brightness. But these are dependent upon the spectral response of the film; this might not be comparable with fish or man. Thus photographic representation gives only an indication of the actual situation.

Despite there remaining some optimism about the value to be had from colouration of nets, there has been considerable research into this field from various aspects over the past century. With much of the work being carried out in Japan and Eastern Europe.

Previous work in this field has taken 2 main forms; trial fishing and experimental estimates of visibility of netting when viewed by man or fish. In general the results from both are in agreement. (Baronov, 1924; Fridman, 1969; Kuike, 1958)

For a net to catch fish we must assume that the fish has either not seen the net or it has paid no attention to it. (Andreev, 1962; Baronov, 1924; Blaxter, 1970; Blaxter, Parrish and Dickson, 1963; von Brandt, 1972; Burgess, 1980; Fridman, 1969; Nikonorov, 1973; Nomura, 1967; Nomura, 1959). According to von Brandt (1972) and Baronov (1926) we cannot assume that the colour alone of the netting will attract fish into the net although it is recorded that Somalian fishermen attach bait to the meshes and Congo fishermen weave coloured pearls into the netting in attempts to attract fish into the net.

For invisibility the netting must be the same colour and shade as the light coming from the background against which it is being viewed, but due to the nature of light under water this requires the net to be lightly coloured when viewed from below and dark when viewed from above and when viewed horizontally it must be of an intermediate shade. The colour also varies with water mass, depth and may vary with direction viewed. With the convex surfaces of twine these requirements for invisibility are technically impossible, but the possible advantages of it in merging with the background can be seen when observing fish. (Baronov, 1924; Blaxter, 1970; Fridman, 1969). So nets should be given an intermediate medium shade which conceals them as much as possible in that water mass.

Due to the physiology of the eye, light objects, when viewed against a dark background appear larger than when a dark object is viewed against a light background. Therefore, as perfect matching is impossible, netting should be darker than the background rather than lighter. So ideally the net should be coloured so that when viewed from above it merges with the background but when viewed from below appears darker than the background. (Baronov, 1924).

With increasing transparency of the water the colour of least visibility becomes darker, and as the water becomes more turbid the light becomes more diffuse and the optimum colour becomes lighter (Andreev, 1962; Baronov, 1924; von Brandt, 1972; Fridman, 1969). Murphy (1959) records that also gill net catches of albacore in N. Pacific also increase with turbidity whereas catches by troll lines fall with loss of transparency of the water. Nikonorov (1973) records similar effects of turbidity on the catch of herring in drift nets. Similarly, with depth the optimum colour gets lighter and according to Fridman (1969) becomes white at 10-15 Secchi disc depths regardless of water transparency and he also considers white to be best when viewing the net from below against bright downwelling light in relatively transparent water.

An alternative way of achieving invisibility is to be transparent, this is the principle on which monofilament and multimono net materials are designed. (Angelson and Huse, 1979; Von Brandt, 1972; Larkins, 1963, 1964; Steinberg, 1963; Tran-Van-Tri and Ha-Khac-Chu, 1963)

On the assumption that what man sees is comparable with what fish see, there has been some observations of netting under water by man. Inoue, Nishizawa, Tamuriai and Kudo (1958) set up a tank and measured the visual range of different colours and thicknesses of net twine in water of different turbidities. Each was illuminated by a lamp with a

colour filter directed through the observation window at the end of the tank. The twine colours were French grey, Grey and Buff.

The results when viewed with a green filter showed that the thicker twine was more visible than the thin, the buff was most visible followed by the thick grey twine, the thick French grey, the thin French grey and least visible was the thin grey twine. The visible ranges decreased with increasing extinction coefficient (k) of the water.

Similar results were obtained when viewed with the yellow filter. When viewed with blue or violet filters then the thin French grey twine became less visible than the grey.

I am unsure as to how applicable these results are to practical net designing because the visible ranges were measured for the side of the twine nearest the source of illumination. The observations were made against the tank background with artificial illumination from a point source and coloured filter rather than using more diffuse natural illumination.

Other work has been conducted in situ, e.g. C.C. Hemmings (1965) conducted experiments off Malta and in the Moray Firth. Netting was mounted on a wire frame 3 m above the seabed and divers recorded the horizontal range of visibility of each colour. At 10 m depth off Malta with attenuation coefficient $c = 0.161\ m^{-1}$ and extinction coefficient $k = 0.0607\ m^{-1}$ the order of increasing visible range of the coloured nets was brown, black, orange, green and white. In 30 m with $c = 0.144\ m^{-1}$; $k = 0.056\ m^{-1}$ the order was orange, brown, green then white. The change in the sequence of visibility of the nets is changed because of selective absorption of long wavelength light by water. This makes orange much darker and thus least visible. It is also worth noting that different divers made different assessments of

visible range but all gave the same sequence of colours, and the water background was considered to be dark rather than light as the order of visible ranges against water background were similar to those achieved when observed against a black background. When viewed against a white background it gave a reverse order of visibility.

Similar experiments were carried out in the Moray Firth in 10 m of water on 4 occasions. The results showed a very close correspondence between the visibility of the nets and the black body distance used to determine c and k. The order of visibility ran from orange being least visible to black, green and brown having similar visibilities, their order varying with different values of c and k experienced at each occasion. The most visible being white. The orange net was least visible against the green water background as the brightnesses are nearly equal. This result suggests that brightness contrast is much more important than colour contrast, even at shallow depth were there is sufficient illumination for colour vision to exist.

In the Mediterranean where there was much stronger illumination brown and black were less visible than orange which appeared too bright. These results are important in that they show that the optimum colour changes with depth and turbidity and that in clear water the horizontal background is darker than in turbid water due to the lesser degree of scattering of light in clear water.

Park and Park (1962) mounted netting on horizontal wooden frames, each dyed either white, cutch brown or with a 2% or 8% solution of black, blue, grey, green, red, pink or yellow. The frames were lowered into the ocean and viewed through a glass bucket until the netting became invisible. The results gave cutch brown and grey (8% soln) as having the least visible range and the order of increasing visible range as blue (8%), green (8%), black (8%), black (2%), red (8%),

blue (2%), grey and green (2%), red (2%), pink (8%), pink (2%), white, yellow (2%) then yellow (8%). They claimed that these results show that grey and black are the best colours for gill nets, etc. as they are least visible, and that brightly coloured nets such as yellow or white would be best leaders to a trap net. In these claims they have not considered that fish will approach the net from the side and the visibility when viewed horizontally will tend to be different to that when viewed from above.

In more recent research by Angelsen and Huse (1979) pairs of panels of netting were mounted vertically and viewed by a horizontally mounted low light T.V. camera at a distance of 1.5 m. The whole rig was lowered into the North Sea. The results were that pale green monofilament was slightly less visible than a yellow-green monofilament and these were invisible at a depth greater than 40 m. Of the multifilaments blue was least visible followed by red-brown, black, yellow and the most visible was white. Pale grey multimono was slightly more visible than blue multifilament. In general dark multifilaments are less visible than light ones and monofilament nets are less visible than multimono nets.

When the rig was tipped so the netting was viewed against sea surface the light coloured multifilaments become invisible, dark multifilaments were easily seen and the visibility of multimono and monofilament appeared to be unchanged.

When observed on a light coloured bottom of sand and gravel at 38 m with an illumination of 5 lux pale grey multifilament meshes were clearly visible whilst green was poorly visible, and for multimono the pale grey was poorly visible whilst the green was even less visible.

Their conclusions were that apart from surface nets, dark nets, especially blue or green were preferable but this was based upon human

visual perception and the optical qualities of water at the time of the experiments. With similar apparatus Molin (1963) observed cotton and monofilament net underwater. The cotton was much brighter and more visible. Even earlier work by Ulrich (1951) was conducted along similar lines with an almost identical set up as Angelsen & Huse (1979).

Other researchers, apart from Park and Park (1962), have experimented with the brightness of colours. Hemmings & Lythgoe (1965) set up a frame containing tiles of either grey or sky blue, and of relative brightnesses ranging 0 to 35% where 0 was black. These were observed by dives at a depth of 30 m off Malta with the frame suspended vertically 3 m off the bottom. The results showed the least visible tiles to have a reflectance of 5 to 10%, these having the least brightness contrast with the background. In general the blue tiles were very slightly less visible than the grey ones. A series of blue nets were also dyed and mounted on a wire frame, these also gave a similar range of % reflectance to the tiles with a minimal sighting range at about 7% reflectance. When the netting was viewed at night the visual range dropped dramatically but the % reflectance of the least visible net was similar to that of daytime.

From the results, Hemmings & Lythgoe suggest that a net could be dyed to have optimal reflectance over the range of visible wavelengths, but it needs properly conducted comparative fishing trials to test this, and such a net is only suitable in the water where the original tests were conducted.

Baronov (1924) had carried out a similar experiment to Hemmings & Lythgoe (1965), using an instrument similar to an inverted periscope he was able, at depths of up to 3 m, observe net samples, ranging from white (100% reflectance) through 10 intermediate shades of grey to

black (0% reflectance). He found that the intensity of the least visible was different if viewed towards or away from the sun, i.e. 5.6% and 2.2% respectively. Baronov took this one stage further than Hemmings & Lythgoe (1965), he measured the optimum intensities in two lakes, Lake Krugloe whose waters were turbid and strongly coloured, and Lake Dolgoe whose waters were clear and not coloured. He then conducted trial fishing with 5 different nets whose colour intensity ranged from 2.5% to 85%. The results were in complete agreement with the net of the best contrast catching 8-10 times as much as a white net. Also from the values of optimum colour intensity the results suggest that dark nets are best in transparent water and light coloured nets are best in turbid waters. Further confirmation of this was that dark grey nets in the transparent waters of the Barents Sea during polar days caught several times more fish than white nets. Baronov (1924) also notes that an olive-green net caught perch exceptionally well and that the backs of the perch caught were identically coloured. But as fish in different water bodies and at different depths are differently coloured, then the optimum net colour/shade with best camouflage will also change. One important fact about Baronov's early work is that through trial fishing programmes he has attempted to correlate best catching nets colours to human observations and in doing so has given weight to the assumption that vision in man and fish is comparable. Fridman (1969) reviewed Baronov's (1924) work and attempts to quantify the optimum reflectivity for an "invisible" net as:

$$\text{Reflectivity } \rho n = \frac{n}{\sqrt{t_1 \, t_2}} \cdot \sqrt{\frac{E_1}{E_b}}$$

where n is a proportionality factor ($n \simeq 1.2$)

t_1 and t_2 are factors allowing for photometric properties of the surface of the elements and the special features of the visual perception of the fish.

E_l and E_b are the illuminances of the lower and upper horizontal planes.

The values of these terms are dependent upon depth, transparency of the water and predominant illumination at the time of calculation.

The practical value of such a calculation is very limited as it is based on unsteady factors, e.g. illumination levels and other data which is difficult to obtain and whose validity I question, e.g. t_1 and t_2.

Other researchers have used observations of fish in tanks with nets.

Konda, Koike and Ogura (1958) produced a set of three papers on observations of fish near nets in a swimming pool, and looked for "barrier" effects rather than lack of them. With horse mackerel (Trachuras trachurus), sand smelt (Atherina elymus) and carp (Cyprinus carpio) the barrier effects were red > yellow > green whilst the effects of black, grey and white depended upon species. The numbers of fish passing through the red, yellow or green nets appears to be related to the colour rather than the intensity of the colour.

With rainbow trout (Salmo gairdnerii irideus) they found that colour caused different reactions, but depth of one colour appeared to have no effect. The effectiveness of the barrier decreased in the order red, yellow = orange, blue, green. The blue and green having the least contrast with the blueish sides of the pool. Also black was an inefficient barrier.

The practical use of this type of work is limited and is based upon artificial conditions and using large mesh so as not to catch the fish as they passed through. Koike, Konda and Ogura (1958) in similar tests concluded that for rainbow trout in daylight increased barrier effects of net colours were blue-green, grey, cutch-brown. The order

in twilight was grey, blue-green, cutch brown. This they suggest implies that the order will change with weather conditions. They conclude that the tendency of fish to be tangled in the net in twilight correlates with the visibility of the netting to the human eye and from the results suggest that as salmon nets are usually fished at night the cutch-brown net will not fish efficiently.

Blaxter, Parrish and Dickson (1963) review their earlier work in this field. Using herring in a grey tank they tested the effectiveness of different barriers across the tank. Their main results were that thick twine could be placed further apart than thin twine for equivalent barrier effects. The effectiveness of one colour twine was independent of material. They found that black and green were better than grey netting as a barrier as they had greater contrast against the grey tank walls. Unknotted meshes of netting proved a better barrier than either vertical or horizontal strands. Monofilament was ineffective as a barrier. For an effective barrier the distance between strands was found to be proportional to the length and therefore possibly age of the herring.

They then altered the light intensity to simulate dusk and night. The findings were that an efficient barrier in daylight became less efficient as light intensity fell, but colours that contrasted well in the day remained better barriers at a lower light intensity than poorly contrasting colours. The visible threshold intensity being in the order of 4×10^{-4} W_{cm}^{-2} s^{-1}. Also an air bubble curtain was used and though effective as a barrier in the day it was less effective at night, suggesting that visual stimuli are perhaps more important than pressure (sound) stimuli. Blaxter et al (1963, 1965) in the discussions compared the tank results with light intensities found on the fishing grounds. These suggest that the in situ summer light intensities are above the visual threshold and therefore fishing is relatively

inefficient as the nets pose a slight visual barrier to the fish. Von Brandt (1972) confirms that monofilament in practice is relatively invisible as the tank tests showed and records daytime catches of herring in the Baltic, but one major drawback is that monofilament nets tend to be very bulky (von Brandt, 1972; Blaxter & Parrish, 1965) and cause damage to the fish. But trial fishing does have one drawback, that is nets tend to become saturated and as discussed by Kennedy (1951) from his trial fishing with cotton gill nets treated with copper oleate which dyes them light blue. When fishing in the Great Slave Lake, Canada, he found that doubling the fishing time did not double the catch. In general for each additional period fished the additional catch dropped as the net became saturated.

Several researchers recorded the behaviour of fishes near fishing nets. Aslanova (1958) records that in the Black Sea and Sea of Azov, anchovy react to a strip of white netting at 1.5 to 2 metres whereas long finned mullet, horse mackerel and sprat react at 3-4 m. For blue netting the reaction ranges changed to 0.3 to 0.5 m and 1 to 1.5 m. In general dark coloured nets catch best; with dark nets catching 2.5 times as much as white nets in the Southern Caspian Sea. In the Aral Sea steel grey nets caught most with in general dull tones catching more than bright tones. In Yenisei Gulf dark grey outfished white with catches being indirectly proportional to transparency. Violet-brown and brown nets fished best in the Barents Sea during the polar day; whilst at night there was no apparent difference with colour. Finally, he found that in the very low transparency waters of the Northern Caspian Sea white nets caught most at night whilst the best colour during the day was brown and catches increased with reduced transparency of the water.

Protasov (1968) also recorded the ranges at which anchovy in the Black Sea reacted to coloured nets seen against the blue-green waters. Blue-

green net was least visible at 0.5 - 0.7 m, dark blue 0.8 - 1.2 m, dark brown 1.3 - 1.5 m, grey or black 1.5 - 2.0 and white was 2.0 - 2.5 m. These ranges appear to be slightly larger than recorded in the earlier work with anchovy in the Black Sea by Aslanova (1958).

Some interesting research was carried out in the Norwegian Lofoten gill net fishing for cod (Sundnes, 1964). Using sonar it was found that cod shoals broke up near newly laid gill nets by day. Similarly Leggett and Jones (1971) found that ultrasonically tagged American shad (Alosa sapidissima) avoided drift nets even on moonless nights, possibly by detection of net vibration or from fish already caught (Kennedy, 1951).

Other research by comparative fishing with nets of different colours, brightness and materials have been carried out. (Larkins, 1963, 1964; Koike, 1958; Nomura, 1957, 1961a, 1961b). Nomura (1957) used nine different coloured nets - red, orange, yellow, blue, green, purple, white, grey and black. Then at a depth of 50 metres where the colours themselves are almost lost, he measured the reflective light energy from each colour net and found that the order of colours in order of brightness was white, yellow, green, blue, orange, purple, red, grey and black and in fishing trials found that the relative catches also rose in this order. With the darkest nets catching was best in daylight, but no difference was found at night.

Nomura (1961b) used the same coloured nets mounted randomly in a grid of 10 x 6 panels (7.5 m x 2.0 m) each fished in sardine drift nets about 40 m depth. The visual range in the sea by day was given as 5-6 m. In his analysis he compared neighbouring panels and found that brighter nets tended to catch more, though this effect was not found at night. This at first seems to contradict earlier research which suggests that darker nets are best in relatively clear waters, when looking horizontally or downwards. But sardines being pelagic may observe the nets against the surface illumination, thus bright colours

are least conspicuous. Also, due to selective absorption of certain wavelengths of light by the water different colours have different relative brightnesses at different depths as recorded by Hemmings (1965).

Larkins (1963, 1964) compared catches of salmon (Oncorhynchus spp.) in the north Pacific using gill nets of different mesh sizes of coloured multifilament and monofilament twines. The nets were all identically rigged at 50% and drifted at night. Green multifilament was compared with light blue-grey monofilament, (Larkins, 1963), and dark green multifilament was compared with light grey monofilament (Larkins, 1964). The results showed that monofilament nets outfished multifilament by 2:1, and that sizes of fish, age groups and species caught depended only on mesh size, not colour or material. Similar results were obtained by Tran-Van-Tri and Ha-Khac-chu (1963) and Molin (1963) quotes monofilament outfishing cotton nets by at least 7:1 and multifilament by 4:1.

But what is perhaps more important is that with the nets (Steinberg, 1963) all laced together, the fleet of nets caught more if monofilament nets were next to multifilament nets than if all monofilament nets. This suggests that the presence of a multifilament net and a seam influences the efficiency of a monofilament net.

Nomura (1961a) notes that the effects of seams in a drift net was to lower the catch near it and this effect was made stronger if the two adjacent panels contrasted greatly in colour or brightness. But where one of the panels was darker or cutched it had a higher concentration of fish caught than a lighter or blue coloured net. This suggests that when confronted with 2 nets the fish will avoid the most visible one and tend to try to get through the neighbouring net which in comparison being less visible appears as a window.

This interaction between nets has been observed by Margetts (1967) and

in his paper on the use of comparative and experimental fishing as a method of studying fish behaviour in the natural environment he concludes that nets will influence each other and that to overcome this each net should be spaced approximately 2 metres apart. I have followed this advice in the rigging of my nets.

In an earlier comparison of the combined salmon and trout catches in grey, cutch-brown and blue-green drift nets, Koike (1958) analysed the regions bordering a seam between 2 coloured nets separately from the centre of each panel. With salmon and trout catches combined the grey and the blue-green nets caught about the same and the cutch-brown net always caught less. In the seam regions at the edge of the panels the cutch-brown net caught less per unit length than in the centre of the panel. Grey or blue-green nets at the edge of a seam with a cutch-brown net always caught more per length than in the centre of either net. A useful further combination would have been to compare a grey and blue-green seam to see if they influenced the catch in each other.

Method

For trial fishing 8 identically rigged nets were used.

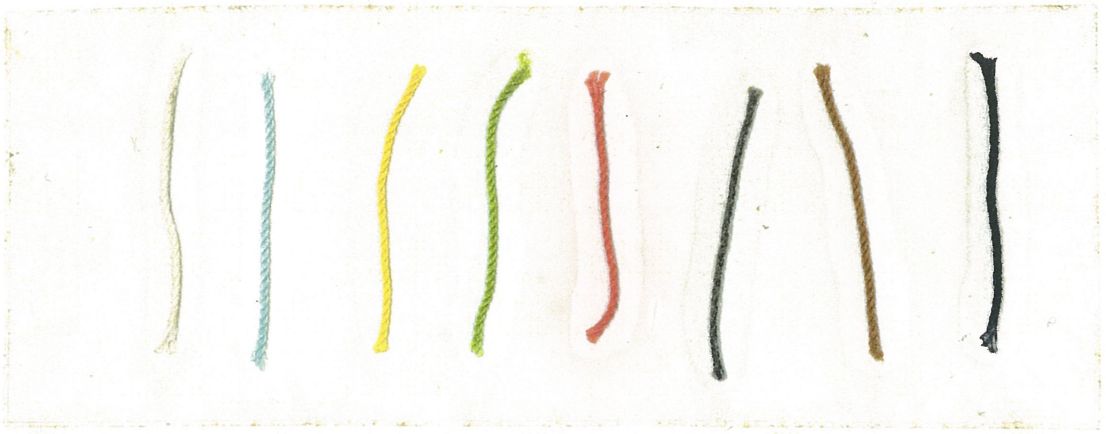
4 bales of white 210d/6 (2Z, R140 Tex) nylon (polyamide) netting of 3" (75 mm) mesh, each bale being approximately 100 yards (91.5 m) stretched length by 50 meshes deep, were divided into 2 x 50 yard (45.8 m) lengths and all edges were selvedged with 210d/9 (3Z, R210 Tex) white nylon twine. After the top and bottom meshes were reeved onto a short length of twine the 8 net panels were ready for dyeing. One was kept white as a control. The other 7 were separately dyed using "Dylon" multipurpose fabric dyes.

The 7 colour dyes used were called Golden Glow 2, Elephant Grey 21, Havana Brown 5, Madonna Blue 18, Scarlet 32, Emerald 25 and Ebony Black 8. For simplicity these shall be referred to as yellow, grey, brown, blue, red, green and black. Each was dyed strictly according to the instructions:- For each 8 oz/250 g of dry netting, use 1 tin of dye and 1 tablespoon (approx 30 g) of table salt to fix the dye. As each length of netting weighed approximately 2 lb (approx. 1000 g) 4 times the specified quantities were used.

The procedure followed was:-

1. Fill a domestic washing machine tub with water and bring to the boil.
2. Dissolve the contents of 4 tins of dye in 4 pints (2 litres) of boiling water, stir well.
3. Add dye to tub, together with the 4 tablespoons of salt, stir well.
4. Add the wet netting to the dye and agitate whilst simmering for 20 minutes.
5. Drain dye away and rinse until water has cleared.
6. Hang netting on washing line to dry.
7. Wash out tub and refill for next colour dye. To remove any possible contamination the lighter coloured dyes were used first followed by progressively darker ones.

To clean the tub after dyeing had finished the machine was run through with hot water, washing powder and a cup of bleach, this removed all traces of dye, but plastic components tended to remain discoloured.



Newly Dyed Twine Samples (210d/9; 3Z; R210 Tex)

With use the nets become slightly discoloured and lose their initial brightness.



Netting Twine Samples after a Period of Use (210d/6; 2Z; R140 Tex)

The nets were all identically constructed. Each net panel mounted with No. 3/16 staple nylon onto 6 mm diameter Greenofil rope. The netting was hung at E = 40%, i.e. 5 x 3" (75 mm) mesh in every 6" (15.25 cm). The reason why it was hung this slack was to enhance visibility of the thin twine by reducing mesh opening and also to improve its tangling properties whilst retaining some ability to gill smaller fish.

Buoyancy for each net was provided by 14 x No. 1003 ($3\frac{1}{4}$") "egg" floats incorporated at 4 foot 6 inches (about 1.37 m) between centres.

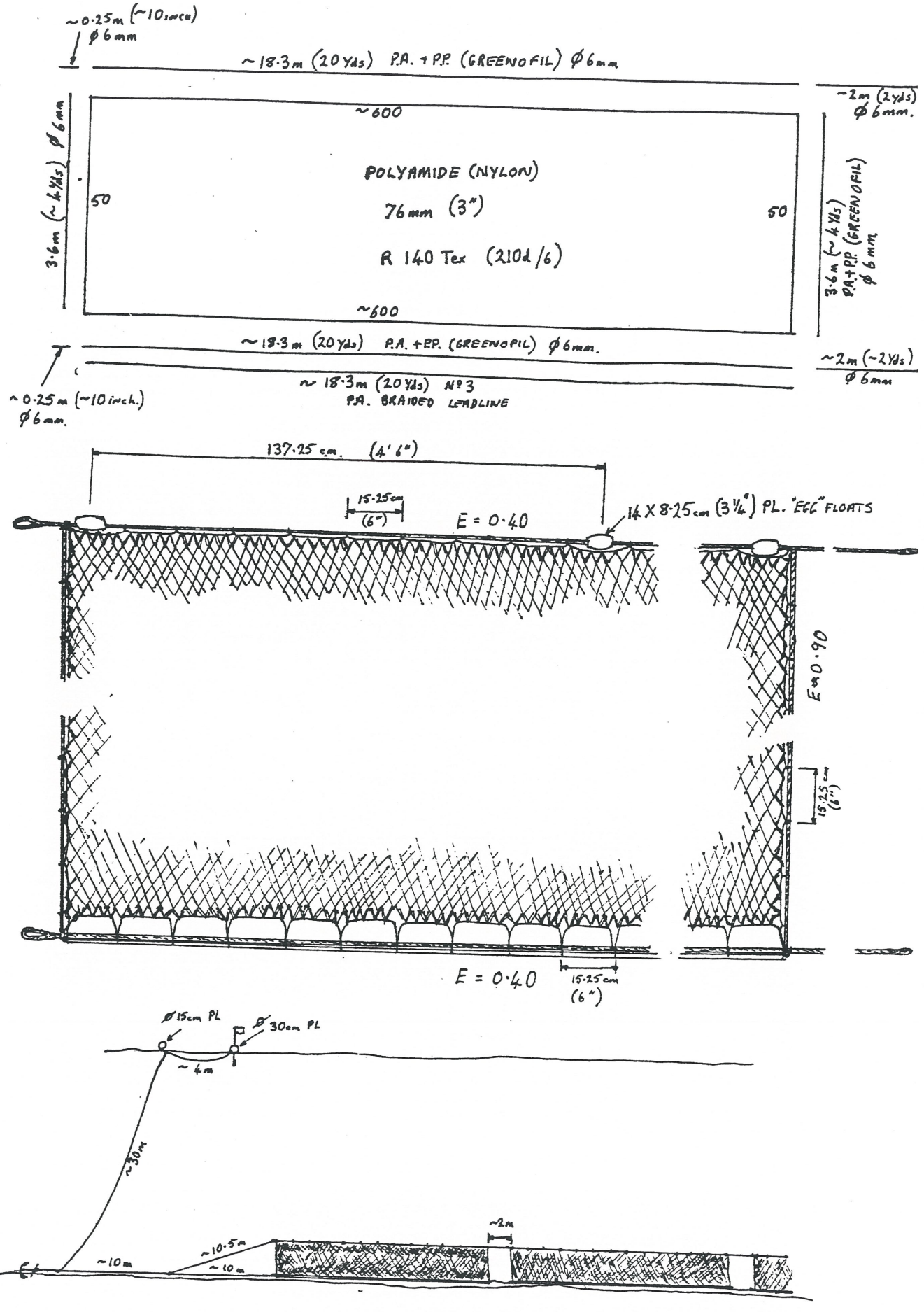
The foot line was weighted with No. 3 synthetic braided (nylon) leadline, mounted alongside the 6 mm Greenofil. The netting was also hung at 40%, i.e. 6" (15.25 cm) between staplings of 5 meshes. If hung tighter it would have given better ground contact for the foot rope, but as the option for surface fishing was required both the foot and head lines were kept equal. This gave each coloured net a mounted length of 20 yards (18.3 m). The ends of the panels were framed with 6 mm Greenofil giving a height of approximately 12 foot (3.6 m). The ends of the head and foot lines were finished off with eyes spliced in one end and with approximately 7 foot (2.2 m) tails (back spliced) in the other. This facilitated easy interchange of nets and the tails kept the nets about 6 foot (2 m) apart thus eliminating any interaction between nets whilst fishing (see figure 1).

The actual rigging of the nets took place between 2 posts approximately 12 m apart, between which was strained a wire with marks every 6" (15.25 cm) to indicate the spacing of the staplings.

Originally the nets were rigged for anchored surface fishing in shallow bays, with the nets suspended from cans on the surface each attached by approx. 1.5 m. of cord to the end of each net. At each end of the fleet of nets was 5 fathom (10 m) of split bridles and a further 5 fathom (10 m) of single bridle to the "fisherman" anchors and buoy lines. This rig was used successfully for the first few settings in the Christchurch Bay area where strong tides and heavy seaweed drifting on the bottom would otherwise saturate the nets and cause them to jump anchor and roll up if bottom set. Fishing was further restricted to the end of the summer by bad weather and the high risk of the gear being run down by pleasure boats during the summer.

Net design and rigging specifications

Fig. 1



This restricted fishing to a few times, these mainly overnight due to being incorporated into a potting operation and the further limitations of the tidal harbour and bar, found at Mudeford, Dorset.

Each time fished the data recorded was:-

- date
- site
- approximate depth
- time fished and whether day or night
- the Secchi disc depth (measured on the sun side of the vessel to illiminate any shadow effects from the vessel)
- the percentage beam transmittance (when the transmittometer was available)
- sea state (calm/rough)
- wind (direction and Beaufort strength)
- sky cover (overcast/cloudy/clear)
- the number of each species of fish caught in each colour
- the total of each species
- the total in each colour
- the total fish caught
- the type of substrate fished over, if known
- it was also intended to measure the levels of surface irradiance (mW) with an Actinograph so that quantitative levels of illuminance at depth could be determined from the attenuation coefficients determined from Secchi disc depth and percentage transmittance. This was impossible due to equipment failure.

The trial fishing was then continued in the Plymouth Sound and Whitsand Bay areas, where the nets were bottom set in an attempt to improve

catches and make it possible to fish a range of depths, in the deeper water, available. Exactly the same information was recorded for each set here as for the earlier fishing carried out in Christchurch Bay, but it must be noted that there may be found to be discontinuities between the two sea areas, and by day or night. These might arise from the difference in water quality between the 2 areas and the changing levels of available illumination at depth.

To further support any results from the trial fishing, both diver and photographic observations were carried out on a few occasions with the nets in situ at 14 m and 28 m depth. Provided fish's vision, as is widely believed, is comparable with that of man (Ali et al, 1975; Baronov, 1924; Lythgoe, 1965; Munz, 1975; De Reuck and Knight, 1965; Stell, 1975 and Tansley, 1965), then there should be a correlation between observed visibility of the netting and the catch rates for each colour net. Determination of net visibility was by a team of divers, who each in turn determined with a tape measure and recorded on a slate what they judged to be the maximum horizontal visual range at which each net was just visible, when viewed against the water background. Also recorded was the "Horizontal Black Body" range for a diver in a black neoprene wetsuit. This gives an approximate value of the attenuation and extinction lengths; $\ell_c = \frac{d}{4}$ and $\ell_k = \frac{d}{1.5}$ (Duntley, 1962; Hemmings, 1965).

As a safety precaution during any diving upon the nets the nets were set across tide so as to enable the divers to work on the down tide side to reduce the risk of being swept into the netting. All divers were experienced and familiar with the type of gear. They worked in teams of 2 (or 3), each group carrying a line attached to a "Surface Marker Buoy" and each diver was fully equipped with safety equipment including a sharp knife, for use if required. On board the diver

standby vessel were a pair of fully equipped standby divers and a dive marshal who logged all divers in and out of the water and recorded bottom times and maximum depths, so as to avoid the necessity of decompression stops. On each occasion the diver vessel was skippered by a member of the college staff who held a Master Mariner's certificate and who was also an experienced diver.

Similar procedures were followed in photographic observations which were usually carried out concurrently with visual range determinations. Using a Nikonos MK II, Calypso underwater camera, Kodak A.S.A. 400 Ektachrome, colour transparency film and a suitable light meter. Each colour net was photographed at a shutter speed of 1/30th with an actual range of 1.5 m (1.0 m focal length) as determined by a 1.5 m long weighted rod. The correct aperture determination for available light was made by taking a light meter reading off a black neoprene glove and then set the camera at 2 stops above this reading, e.g. if light meter reads f/1.4 set the camera to f/2.8. This technique was suggested by Mike Wiles, Lecturer in Photography, College of Art and Design, Plymouth.

With additional frames I bracketed below and where possible above this setting. Only one setting was eventually used as being representative of the actual situation. The validity of a photographic reproduction of the conditions is questionable, due to the difference in spectral response of the film emulsion and the eyes of both man and fish. This will be discussed later. (see Appendix)

Definition

Fundamental Quantities:-

Wavelength (λ). The distance between two successive points of a periodic wave in the direction of propagation. The wavelength of monochromatic radiant energy depends on the refractive index of the medium. Unless otherwise stated, values of wavelengths are those in air.

Unit: m. 1 nm = 1 n = 10^{-9} m.

Sun Zenith Distance (i). The angle between zenith and the centre of the sun's disc.

Radiant Flux (F). The time rate of flow of radiant energy.

Unit: watt, W = Joule/second.

Radiant Intensity (I). The radiant flux emitted by a source, or by an element of a source, in an infinitesimal cone containing the given direction, divided by the solid angle of that cone.

Unit: watt per steradion, $W/sr = dF/d\omega$

Radiance (L). Radiant flux per unit solid angle per unit projected area of a surface.

Unit: watt per square metre and per steradion, W/m^2sr

$$L = d^2 F/dA \cos \varepsilon \, d\omega$$

Irradiance (E). The radiant flux incident upon an infinitesimal element of surface containing the point under consideration, divided by the area of the element.

Unit: watt per square metre, $W/m^2 = dF/dA$.

Properties of the Sea:-

Reflectance (ρ). The ratio of the reflected radiant flux to the incident radiant flux.

$$\rho = F_r/F_o$$

Irradiance Ratio (R). The ratio of the upward to the downward irradiance at depth in the sea.

$$R = E_u/E_d$$

Transmittance (T). The ratio of the transmitted radiant flux to the incident radiant flux.

$$T = F_t/F_o$$

Beam Transmittance. The transmittance for a beam the diameter of which is small compared to its length.

The relation for homogeneous medium: $\ln T = cr$

Absorptance (A). The ratio of the radiant flux lost from a beam by means of absorption, to the incident flux.

$$A = F_a/F_o$$

Scatterance (B). The ratio of the radiant flux scattered from a beam, to the incident flux.

$$B = F_b/F_o$$

Attenuance (C). The ratio of the radiant flux lost from a beam by means of absorption and scattering, to the incident flux.

$$C = F_c/F_o$$

$$1-C = (1 - A)(1 - B) = T$$

Absorption Coefficient (a). The internal absorptance of an infinitesimally thin layer of the medium normal to the beam, divided by the thickness (Δr) of the layer.

Unit: m^{-1}; $a, = -\Delta A/\Delta r = -\Delta F/F\ \Delta_r$

For homogeneous medium: $ar = -\ln (1 - A)$

(Total) Scattering Coefficient (b). The internal scatterance of an infinitesimally thin layer of the medium normal to the beam, divided by the thickness (Δr) of the layer.

Unit: m^{-1}; $b = -\Delta B/\Delta r = -\Delta F/F\Delta r$

For homogeneous medium: $br = -\ln (1 - B)$

(Total) Attenuation Coefficient (c). The internal attenuance of an infinitesimally thin layer of the medium normal to the beam, divided by the thickness (Δr) of the layer.

Unit: m^{-1}; $c = -\Delta C/\Delta r = -\Delta F/F\Delta r$

$$c = a + b$$

For homogeneous medium: $cr = -\ln (1 - C)$

Refractive Index (n). The phase velocity of radiant energy in free space divided by the phase velocity of the same energy in a specified medium.

It is equal to the ratio of the sine of the angle of incidence (i) (in vacuo) to the sine of the angle of refraction (j)

$$n = \sin i/\sin j$$

Optical Length (τ). The geometrical length of a path multiplied with the total attenuation coefficient associated with the path.

$$\tau = cr$$

Instruments

Light measuring instruments are usually based upon a selenium photo-voltaic cell. This gives a linear relationship between light and photo-current provided that (1) the cell is not exposed to greater than 1.5% of the brightest daylight (2) the external resistance of the galvanometer is low ($<50\Omega$) in the brightest condition. This means that in the upper strata of the water the light is first reduced by means of neutral filters. (N.G. Jerlov, 1965)

A further factor, when using the selenium cell is that its response varies with wavelength of incident light, being fairly insensitive to red light which the water absorbs strongly.

For satisfactory use of the photocell it should be used with colour filters to restrict the spectral region of response. This is because the sensing system which responds differently to different wavelengths is being used to measure light which becomes increasingly monochromatic with depth. (Woods & Lythgoe, 1976)

The way the photocell is used is dependent upon what is being measured. The 2 basic instruments using a photocell are (a) The Cosine Collector (b) The Gershun Tube.

(a) The Cosine Collector (see Fig. 2)

This is used to measure irradiance striking a horizontal surface. The effect of incoming flux is dependent upon its angle of incidence on the surface, therefore varying with the cosine of its angle to the normal.

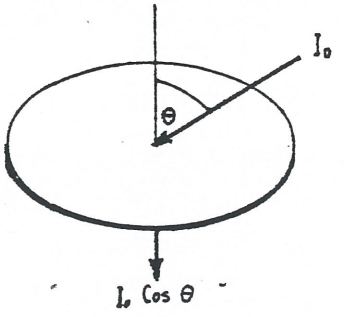


Fig. 2

Cosine Collector

Thus at $\theta = 0$ the incident intensity is unchanged

at $\theta = 90^{\circ}$ the effective incident intensity is zero.

So in effect it accepts components of the incident light through an acceptance angle of 180°.

In practice a perfect cosine collector does not exist, but opal glass transmits light roughly proportional to the cosine of its angle of incidence.

Using an appropriate filter housed between the cosine collector and photocell the appropriate intensity of irradiance of that wavelength can be measured.

If mounted horizontally facing upwards it can be lowered into the sea to measure the intensity wavelengths of downwelling diffuse light at each depth. Similarly if inverted it will measure the intensity of the diffuse upwelling light at each wavelength and depth.

From the irradiance values at each depth, the extinction coefficient (k) can be calculated from the relationship. $I_Z = I_o e^{-kZ}$
From this sort of measurement of upwelling and downwelling light it has been found that light becomes increasingly diffuse with depth and the difference between upwelling and downwelling light gets less. This being due to scattering in the water mass. (Jerlov, 1965; Williams, 1970, 1973; Woods & Lythgoe, 1976)

(b) <u>The Gershun Tube</u> (see Fig. 3)

The principle of this is to reduce the angle of acceptance to approach 0°

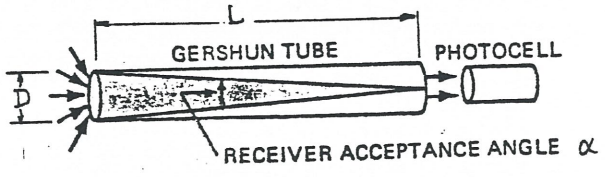


Fig. 3 Gershun Tube

$$\text{Tan } \alpha = \frac{D}{L} \simeq \alpha$$

The long tube is blackened on the inside so that only light travelling in the general direction of the tube (angle = α) is emitted at the other end. By lengthening the tube relative to its diameter the acceptance angle α is reduced and the intensity on the photocell is less.

This system is generally approximated by a lens aperture arrangement. (see Fig. 4)

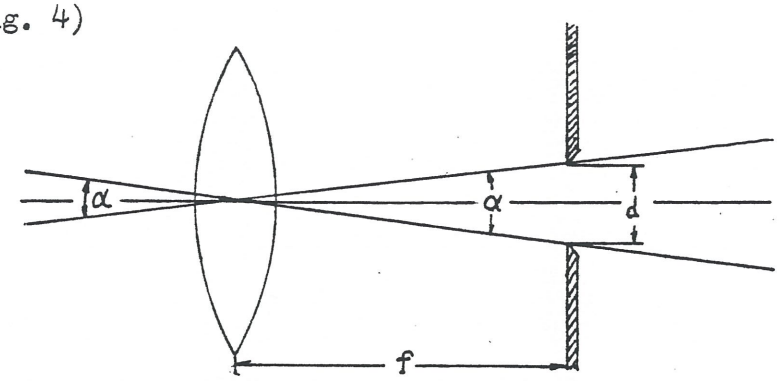


Fig. 4 Lens aperture approximation to Gershun Tube

The acceptance angle α of this system is

$$\alpha = \text{Tan}^{-1} d/f$$

where d is diameter of aperture
f = lens focal length
α = acceptance angle

Thus the acceptance angle can be varied by altering the lens or the aperture diameter.

The application of the Gershun tube includes (i) the Beam transmittance meter and (ii) scatter measuring devices.

(i) Beam transmittance

To form an image it requires light to travel in a straight line, the passage of such a beam is effected by absorbance and scattering. This is expressed as beam attenuation losses which are described by the coefficient c.

Beam transmittance meter consists of a light source and lens system to give a collimated beam, a path length within the water medium and a lens-aperture system to limit acceptance angle to the photocell. The Gershum tube may be used but its length must be included into the path length and it must be assumed that the black inside surface of the tube is a total absorber, i.e. reflectance (ρ) = 0.

Using 2 path lengths the loss of intensity due to beam attenuation can be found. $\ln = 1_o\ e^{-cL}$ where c = beam attenuation coefficient,

where $c = a + b$: a being the absorption coefficient
b being the scattering coefficient

(ii) Scattering measurement (Nephelometers)

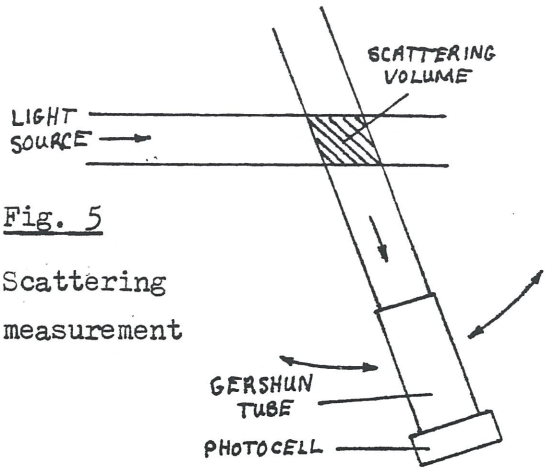


Fig. 5

Scattering measurement

This consists of a light source and a Gershun tube and photocell which can be moved about the scattering volume, thus measuring the scattering through each angle. (see Fig. 5)

Being that the photocell is always used in association with a filter, the scattering can be specified for both wavelength and scattering angle.

The scattering volume is determined by the source beam and beam that is accepted by the Gershun tube.

The main problem with this kind of instrument is due to secondary scattering and determination of the exact size of scattering volume. Theoretically from this the scattering coefficient (b) can be determined. Much of the more recent work on development of a nephelometer has been done by N.G. Jerlov (Jerlov, 1968). This is discussed in J. Williams, 1970, 1973.

The other problems with a system using photocell and filters are
(1) immersion effects :- in water, glass reflects better in water due to change of refractive index so there is a reduction of sensitivity of the system when immersed. (Jerlov, 1965; Williams, 1970)
(2) the band width of transmission of different filters. This tends to also shift towards the blue with increasing depth of operation. The problem of beam width of filters can be largely overcome using an interference filter. This is a series of gratings that can be used to isolate a beam of about 5.5 nm bandwidth. (Hemmings & Lythgoe, 1965; Jerlov, 1965)

Other devices used in Underwater Optics

Hemmings & Lythgoe (1965) worked on a diver operated device for measuring the downwelling and background (horizontal) illumination. The device allows the 2 light fields to be displayed together, then the top light is reduced in intensity to equal the side light by a suitable neutral density filter. The optical density of the filter needed to do this is a measure of the relative intensities of the side light to the top light. By viewing the 2 light fields are viewed together through a narrow waveband filter, then the relative intensity of the light from the 2 directions can be assessed on a spectral basis. (see Fig. 6)

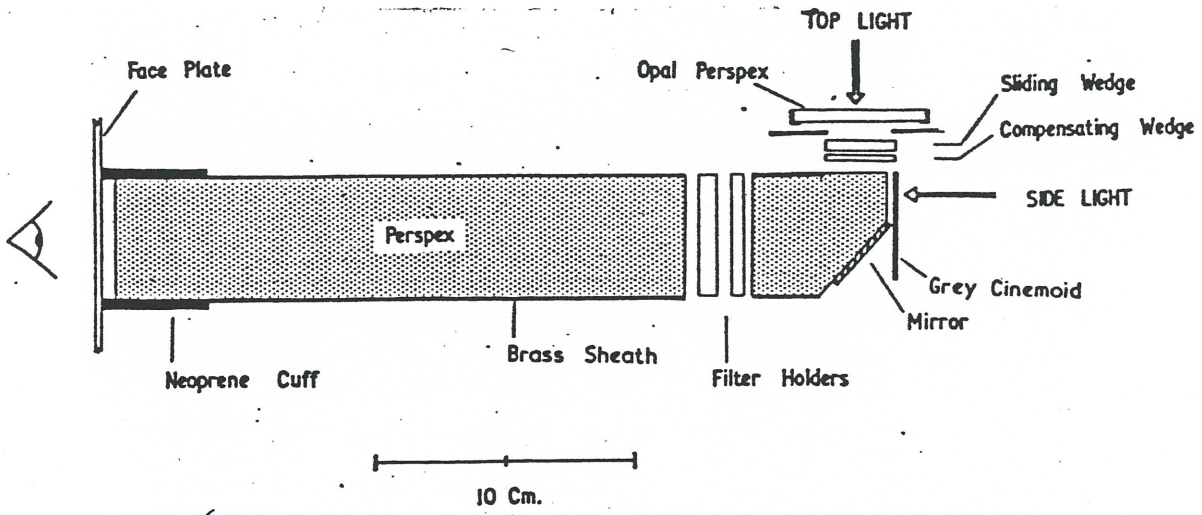


Fig. 6. Diagram of the device used to compare the relative spectral intensity of top light and side light.

Note: Perspex and seawater have approximately the same optical density
∴ no refraction at interfaces.
When top light equals side light
Top light x wedge transmission = side light x cinemoid transmission.
Together with the use of this device was a series of associated experiments in which sighting ranges were taken of coloured tiles and tiles of different shades of blue and grey (Hemmings & Lythgoe, 1965).

Lythgoe (1968) developed a further diver operated device for comparing

the spectral radiance of a flat target compared with the background light. (Woods & Lythgoe, 1976) (see Fig. 7)

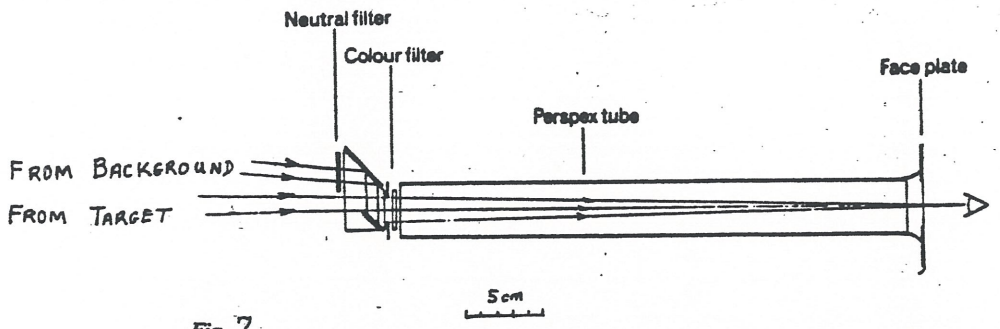


Fig. 7
Plan of a diver-held device that is used for comparing the spectral radiance of a flat target and the water background spacelight. (Woods & Lythgoe 1976)

Visual ranges can be found either by measurement of the visual range from a target along a tape measure or in more turbid waters by the use of a "trombone", this allows a target to be pushed out on a scaled rod until it just disappears. (Hemming & Lythgoe, 1964; Hemming & Lythgoe, 1965; Woods & Lythgoe, 1976)

The Secchi Disc

The Secchi disc is probably the most commonly used device for determining water transparency in oceanographic work, since its introduction in 1866 by Prof. P.A. Secchi (Tyler, 1968). The white disc is lowered in the water until it is just lost from sight. This gives the Secchi disc depth (D), but this is dependent upon various factors including both extinction (k) and attenuation (c) coefficient, disc reflectance (ρ_D), relative amount of upwelling light (U), surface illumination (E_o), radius of disc (r), surface reflectance (ρ_s) and contrast threshold of observer (C_e) at disappearance of disc. Most of these may be specified but this still leaves the loss coefficients (c + k) combined and is also assuming that the water is homogeneous with depth and U is known. (see Fig. 8)

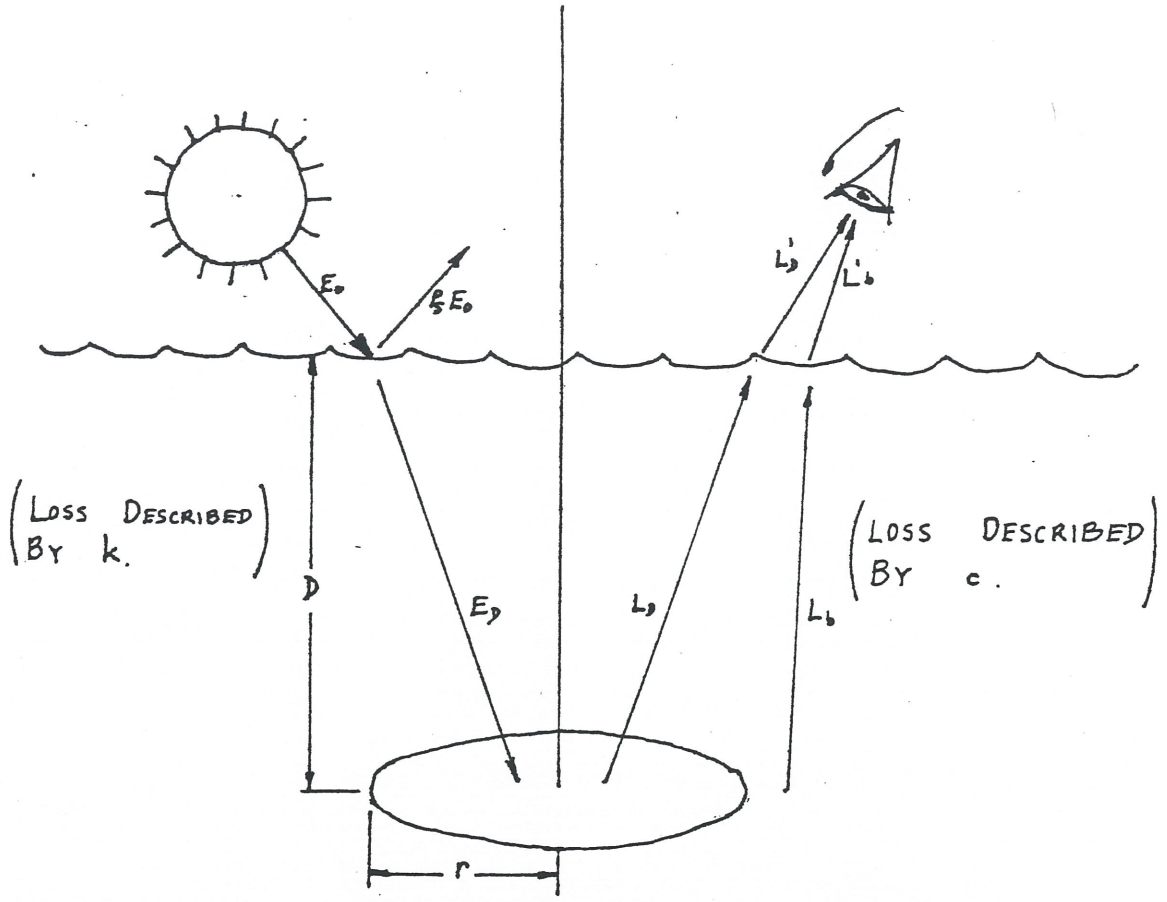


Figure 8 Light values involved in Secchi disc problem

The observation of the Secchi disc is discussed by J. Williams (1970). Taking a perfectly diffusing Secchi disc of radius r and reflectance ρ_D which disappears from sight at depth D and assuming that the water is homogeneous to at least depth D. The surface received an illumination of E_o lumen/m^2 from the sun. U is the proportion of light that is travelling upwards.

So when the disc disappears its inherent contrast at disc depth is C_D

$$C_D = \frac{L_D - L_b}{L_b} \quad \text{this simplifies to} \quad \frac{\rho_D - U_D}{U_D}$$

This is where the flux reflected (L_o) from the disc at depth D is

$$L_o = \frac{E_o (1 - s) \rho_D \exp(-kD)}{\pi}$$

and similarly background producing flux (L_b) at depth D is

$$L_b = \frac{U_D E_o (1 - \rho s) \exp(-kD)}{\pi}$$

The π term results from the assumption that upwelling light is

diffuse.

The apparent contrast (C_e) seen by the eye at the surface is

$$C_e = \frac{L_D^1 - L_b^1}{L_b^1}$$

where flux reflected from the disc and reaching the eye, L_D^1 is

$$L_D^1 = \frac{E_o (1 - \rho s)^2 \rho_D \exp (- (k + c) D)}{\pi (D^2 + r^2)}$$

This describes the loss through attenuation (c) of light from the disc (L_D).

L_b^1 is the light reaching the eye from the background, i.e. that upwelling from the surface plus that light that is reflected from the surface.

$$L_b^1 = \frac{U_o E_o (1 - \rho s)^2 + \rho s E_o}{\pi}$$

Therefore apparent contrast, C_e simplifies to

$$C_e = \frac{\frac{\rho_D \exp [- cD]}{D^2 + r^2} - \frac{U_o}{\pi} - \frac{\rho_s \pi}{(1 - \rho s)^2}}{\frac{U_o}{\pi} + \frac{\rho s \pi}{(1 - \rho s)^2}}$$

Also from Duntley (1962) C_e can be expressed as

$$C_e = C_D \cdot \frac{L_b}{L_b^1} \cdot (1 - \rho s) \cdot \exp (- cD)$$

$$C_e = \left(\frac{(\rho_D - U_D)}{U_D} \right) \cdot \left(\frac{U_D E_o (1 - \rho s) \exp (- kD)/\pi}{U_o E_o (1 - s)/\pi + \rho s E_o} \right) (1 - \rho s) \exp (- c D)$$

$$C_e = \left(\frac{\rho_D - U_D}{U_o + W} \right) \cdot \exp [- (k + c) D]$$

where $W = \frac{\rho s \pi}{(1 - \rho s)^2}$

Tyler (1968) expressed the apparent contrast C_e in terms of the inherent contrast C_D, such that

$$C_e = C_D \exp [- (c + k) D]$$

This is useful because if the disc is not horizontal in the water when viewed from above, then at depth D

$$C_e = C_D \exp [- (c + k \cos \theta) D]$$

and similarly if not observed from above depth D is replaced by range R.

At disappearance, C_e is the threshold contrast (C_τ). This varies with the ambient light and angle subtended by the target at the eye. The human eye needs an angle greater than 13.7 minutes of arc. This is equivalent to a 30 cm diameter (r = 15 cm) disc viewed at less than 100 metres (D). For the angles involved and typical daylight illuminance the contrast threshold may be considered constant at about 0.003. (J. Williams, 1970)

Then substituting in Duntley's contrast equation (1962)

$$C_e = 0.003 = \left(\frac{\rho_D - U_D}{U_o + W} \right) \exp [- (k + c) D]$$

$$\exp [- (k + c) D] = \frac{0.003}{\frac{\rho_D - U_D}{U_o + W}}$$

$$\exp [(k + c) D] = 333 \left(\frac{\rho_D - U_D}{U_o + W} \right)$$

$$(k + c) D = \ln \left[333 \left(\frac{\rho_D - U_D}{U_o + W} \right) \right]$$

$$k + c = \frac{1}{D} \ln \left[333 \left(\frac{\rho_D - U_D}{U_o + W} \right) \right]$$

The term W is dependent upon surface reflectance (ρs), this may be greater than U_o .'. cannot be neglected. But if viewed through a glass bottomed bucket or divers face mask, then the surface reflectance terms and thus W may be disregarded. (Duntley, 1962; J. Williams, 1970)

Alternatively to using a glass viewing plate the disc may be observed

through polarized glasses, this will eliminate the plane polarized part of the reflected light which may be a major portion in some cases.

Thus $k + c = \frac{1}{D} \ln \left[333 \left(\frac{\rho_D - U_D}{U_o} \right) \right]$

and assuming that the water is very deep and optically homogeneous then $U_D = U_o = U$. Therefore it further simplifies to

$$k + c = \frac{1}{D} \ln \left[333 \left(\frac{\rho_D - 1}{U} \right) \right] \qquad \text{(J. Williams, 1970, 1973)}$$

This expression has 3 unknowns, the 2 loss coefficients, c + k and the relative amount of light upwelling (U). This is assuming that disc reflectance (ρ_D) is known.

Note: ρ_D varies from disc to disc and there exists no standard value for reflectance, therefore no standard Secchi disc. (J. Tyler, 1968)

To determine the value of the combined loss coefficients (k + c), U must be determined. This can be done with 2 Secchi discs each with different reflectances ρ_{D1} and ρ_{D2} and with the depths D_1 and D_2 recorded, U may be calculated. Assuming that the water is optically homogeneous there will only be one value for U.

Typically white and black discs would be used for the 2 different Secchi discs due to their extremes of reflectance.

Despite this it still gives a combined value of k + c, these 2 coefficients being inseparable for the Secchi discs.

Determination of k can be done by the use of a photocell at 2 depths. So by Beer-Bouger law:

$$\ln I_1 - \ln I_2 = k (D_2 - D_1) \quad \text{(Walker, 1980)}$$

as done in the earlier Poole and Atkins work on the Secchi disc.

Alternatively as discussed by Tyler (1968) is to use a Secchi disc in

association with a photometer and from the results obtain values of c and k for each value of D for the Secchi disc. These values of c and k are only averages for the water column.

The values of k can be estimated by the relationship

$$k = \frac{1.7}{D}$$

This was originally suggested by Poole and Atkins (1929) from work done in the English channel and has been shown for the North Pacific by G.I. Murphy (1959). J.E. Tyler (1968) states a range of values of kD from 1.305 to 2.22. C.C. Hemmings (1965), and Duntley (1962) gives kD = 1.5.

T. Walker (1980) reviews the use of the original Poole & Atkins (1929) formulae that kD = 1.7 as a universal approximation of k. She revises their calculations, suggesting that their estimate of a constant surface reflectance of 15% was wrong, and that when corrected gave a new relationship that k D = 1.45; suggesting that this ties in better with other more recent work. So with this formula a better estimate of k can be made using only a Secchi disc.

The Secchi disc readings are also influenced by where they are taken. If taken on the shadow side of the ship then the disc is being lowered through the ships' underwater shadow and may not even be in the shadow when viewed. The reason for viewing on the shadow side is usually to reduce surface reflection, but in doing so the Secchi readings become highly variable and useless for determination of c or k. Furthermore Secchi readings done in this way cannot be accurately compared.

For comparable Secchi disc readings they must be done out of shadow influence, with a disc of known reflectance and lowered vertically with the disc horizontal and threshold contrast specified. Possibly the best way to do this is with a skin diver viewing through a face mask

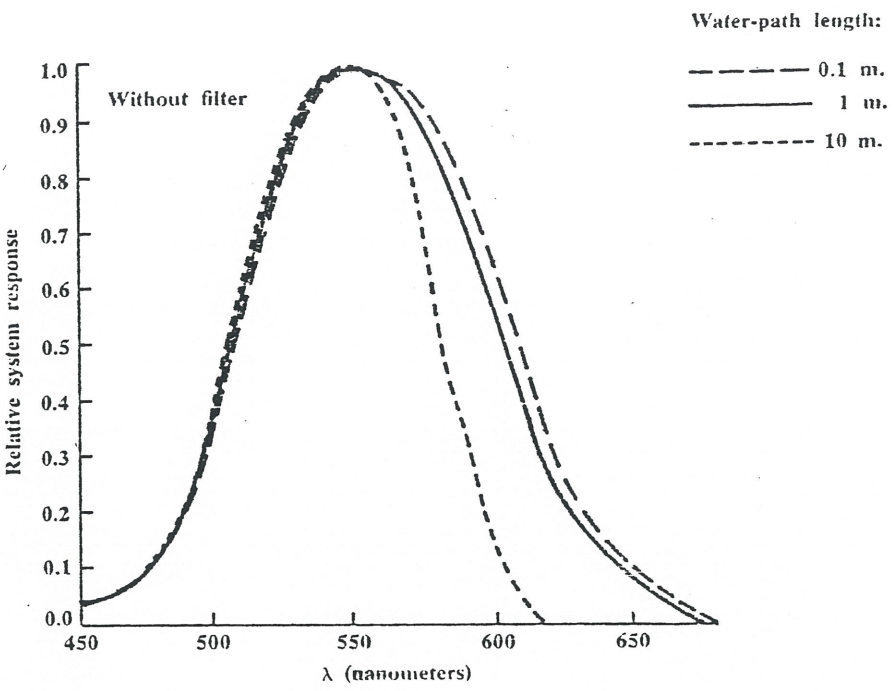
due to only a very small shadow being cast, while on board ship c and k can be determined. (J.E. Tyler, 1968)

A further aspect of Secchi disc measurements is discussed by J. Williams (1970, 1973). Water being a selective absorber of light, thus with depth the spectrum of light transmittance changes, rapidly losing the red end of the spectrum due to absorption. The human eye (daylight orientated) has a different response being symetrical around a peak of 555 nm and thus does not respond equally to all wavelengths. Similarly all optical systems have their own response curves.

As the eye response curve is different to the water transmittance curve it means that any Secchi disc (or optical) measurements will be weighted due to the difference between photopic eye response and transmittance response of the water. Also the response will vary with path length, with the eye responding to the red end less with increasing path length. Furthermore, the apparent attenuation coefficient (c) varies markedly with path length of water being measured so any attempt to extrapolate transparency readings, taken with the Secchi disc ranges measured will be in error due to the variability of c.

So apart from the Secchi giving only the combined loss coefficients and these dependent upon both water turbidity and range. This second problem can be overcome in a similar way to that used in other optical systems. If the Secchi disc is viewed through a filter that passes wavelength found in the transmittance and perceivable by the eye then the relative response of the sunlight-photopic eye-water optical system does not alter significantly with depth (see fig. 9). Furthermore, the attenuation coefficient remains fairly constant over the range of depth at the filter transmittance wavelength.

Therefore any Secchi disc measurements should ideally be made by a diver using a band-pass filter face mask and any results obtained being wavelength specific. At best from this you only get a combined value of c + k



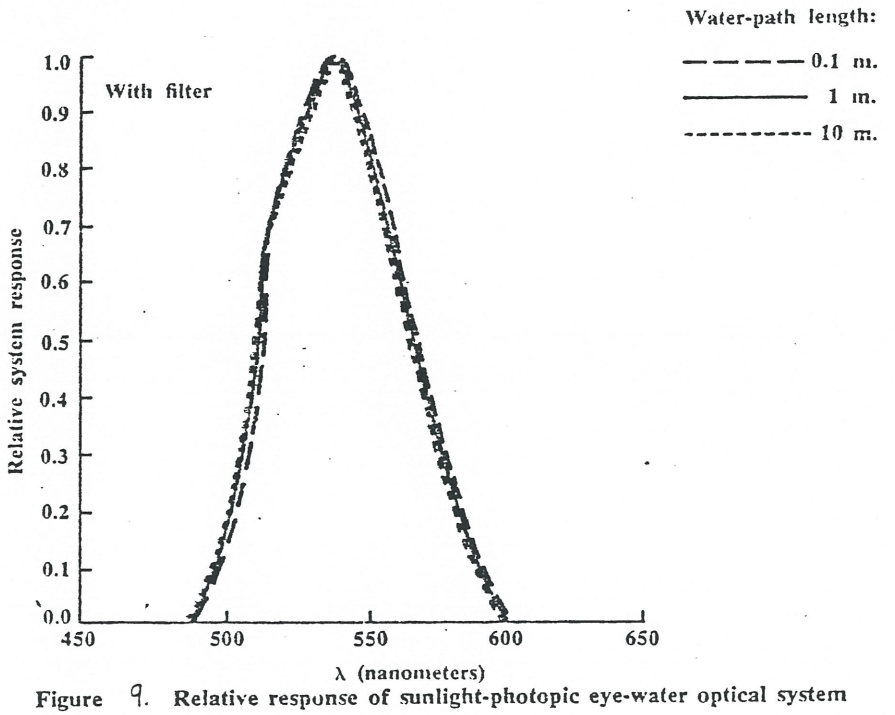


Figure 9. Relative response of sunlight-photopic eye-water optical system with and without Wratten #61 filter.

and to use these one of the coefficients must be determined independently by another optical instrument.

But despite these problems of non-standardization of a Secchi disc and what is actually being measured, the Secchi disc is often used as an indication of "transparence" due to tradition and the simplicity of operation. (J. Tyler, 1968; J. Williams, 1973)

An improvement on the Secchi disc for measuring contrast and visual range would be the use of a black disc. By definition this would have a constant inherent contrast of -1 due to having negligible reflectance and being viewed as a silhouette. This has been used to estimate c and k from the visual range of black silhouetted targets, e.g. divers when viewed horizontally.

According to Duntley (1962) and Hemmings (1965) rules of thumb are

(1) most objects can be sighted at 4 to 5 times the distance

$$1/(c - k \cos \theta)$$

(2) large dark objects seen as silhouettes against a water background can be sighted at a range $4/c$ when viewed horizontally

(3) in some natural waters $c = 2.7\ k$ (not a linear relationship, Walker (1980))

In such waters the downward range of sighting of most objects = 7/8 the horizontal sighting range of large dark objects. (G.I. Murphy, (1959) found no significant difference in horizontal and vertical ranges in the North Pacific).

(4) large dark objects can be sighted at a horizontal visual range of $1.5/k$.

Woods & Lythgoe (1971) discuss the use of the "Black body distance" compared with the Secchi disc and conclude that it is far superior to the Secchi disc, in all but convenience, as black body distances can be interpreted in physical terms, i.e. $C_r = C_o . \exp(- c_r)$

where by definition $C_o = -1$, r = range as length that black object can be seen by diver, C_r = threshold contrast when sight is lost (0.02). Therefore attenuation coefficient $_c$ can be determined directly unlike Secchi disc measurements.

THEORY

Colour of the sea

The visible spectrum in humans covers the range from about 380 to 670 nm but its limits are ill defined. In fishes the range may be slightly different and their peaks of sensitivity are thought to be slightly away from the green part of the spectrum, as is found in man. This being thought to be largely due to the different environmental constraints in which fish have evolved.

Incident light on the sea surface from the sun and sky covers the spectral range from 290 to 2500 nm, but we need only concern ourselves with the visible spectrum, i.e.

Ultra violet	< 400 nm	
Violet	400–420 nm	Visible to human eye (J. Williams, 1970)
Blue	460–480 nm	
Green	525–545 nm	
Yellow	565–585 nm	
Orange	590–610 nm	
Red	650–670 nm	
Infra red	> 670 nm	

Not all the light that is incident upon the surface enters the water, this is due to reflection and is largely dependent upon angle of incidence, i.e. zenith distance of source (sun) for smooth water surface, and relative refractive index of water (n = 1.33)

For Direct Solar Radiation

Zenith distance	Reflectance	Zenith distance	Reflectance
0°	2.0%	50°	3.5%
10°	2.0%	60°	5.9%
20°	2.0%	70°	13.2%
30°	2.1%	80°	34.7%
40°	2.4%	90°	100%

This reflection results from the refractive index (n) of the air/water

surface.

$$n = \frac{\sin i}{\sin j} = 1.33 \text{ for water}$$

where: i is incident angle of light to the normal

n is angle to normal of refracted light.

The Fresnel equation gives the reflectance (ρ)

$$\rho = \tfrac{1}{2}\left[\frac{\tan^2 (i-j)}{\tan^2 (i+j)} + \frac{\sin^2 (i-j)}{\sin^2 (i+j)} \right]$$

when zenith distance is 0 (sun directly overhead) this simplifies to

$$\rho = \frac{(n-1)^2}{(n+1)^2} \qquad \text{(after Jerome William, 1970)}$$

The zenith distance of the sun varies according to geographic latitude, season and time of day, and the intensity of incident light is dependent upon scattering and absorption in the air. (H.U. Richter, 1962).

Reflectance of Diffuse Light

The previous case was for direct sunlight, usually however much of the light is diffuse sky radiation. On a clear day the percentage of diffuse radiation ranged from 27 to 67% for zenith distances of 50 to 80°, in summer, and from 15 to 59% in winter. On an overcast day up to 100% of the incident light may be scattered from the sky. For 100% diffused light the surface reflectance would be about 6.6%. With more common partially overcast sky total reflectance would be up to 11% or above. These figures are based on work by Neumann and Hollman (1961) on Long Island Sound, and are therefore not representative of the world wide situation. (Jerome William, 1970).

Practical measurement of the reflectance from the sea surface is difficult to measure directly as it includes light that has been scattered back upwards from the water mass. Though the value of back scattered light can be measured and subtracted from the total reflectance

measured to give the true value of reflectance.

Jerlov (1976) reviews work done upon the effect of sea state, zenith distance of sun and sky cover upon albedo.

In general for a clear sky surface reflection increases with a low sun (large zenith distance); though it does not vary much over small zenith distances (0-40°). Also surface reflectance decreases significantly with wave action for solar zenith distances above 70°, from 0 to 70° reflection increases slightly. For overhead sun, i.e. 0° zenith distance the sea state has no effect upon reflectance. These results being based upon a "rough" sea of Beaufort force 4 wind waves; which is approximately the roughest sea conditions likely to be fished in this project.

For an overcast sky reflectance is less than for calm water over the zenith distances 0° to 30° and above 60°. This effect can be seen from a rough sea appearing darker than a calm sea which is almost the same brightness as the sky, especially on the horizon which becomes ill defined when calm. (See fig. 10)

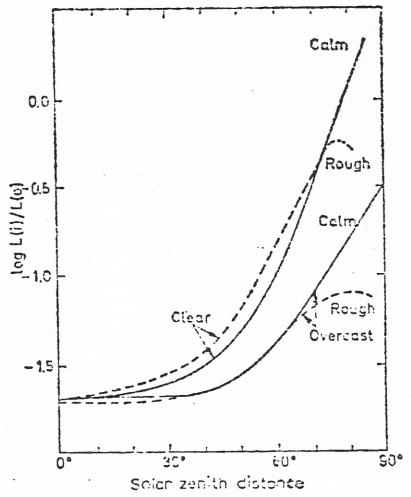


Fig 10 Reflected radiance $L(i)$ divided by the sky radiance at zenith for calm weather and for a Beaufort 4 wind. (After Jerlov 1968)

As % transmittance from the air to the sea = 100-% reflectance (albedo) it means that as the sea gets rougher more light penetrates to below the surface, but this is not to say that light levels will rise at depth as usually increased wind eventually causes more surface turbidity and higher attenuation losses especially in shallow coastal water.

The surface reflectance variation between calm and rough is very small, except at large zenith angles, as experienced at dawn and dusk. Similarly, with cloud cover proportionally less light is reflected when overcast, the small difference is due to the incident light being diffuse. So zenith distances may be considered to be the main influence upon reflectance and thus transmittance into the sea.

As the light penetrates into the water it is scattered, and absorbed at various rates. It is the wavelengths least absorbed which give the water its characteristic colour. The pure water component of the sea water absorbs most strongly in the long-wave region, this means that after a few metres the remaining radiation is largely within the visible and ultra violet wavelengths, see fig. 11.

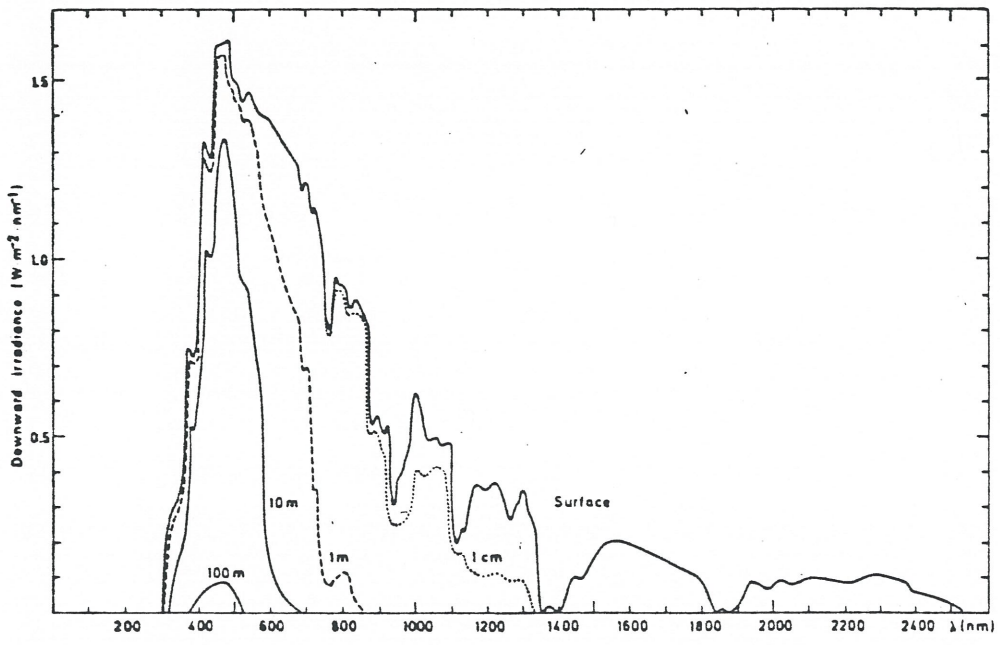


Fig.11 The complete spectrum of downward irradiance in the sea. (After Jerlov 1976)

This absorption reduces the longer wavelengths more rapidly with depth and shifts the resulting colour of the water mass away from the red end towards the blue/green colour of tropical ocean water (largely unproductive), centred around 470 nm. Thus the water behaves as a very efficient monochrometer.

As the water becomes more productive, i.e. increases chlorophyll and other photosynthetic pigments due to phytoplankton and the presence of "yellow substance" the water tends to become greener. This is due to chlorophyll using red and blue light in photosynthesis while reflecting green. The "yellow substance" absorb blue light, but allow the green and other wavelengths to pass. But the water still absorbs the red end of the spectrum most strongly, therefore only green remains, as is seen in the oceans at high latitudes. Near river outlets the "yellow substance" which results from organic decay is still stronger and the resulting water colour is usually green or yellow-green. (Wood & Lythgoe, 1976)

Fresh water of rivers and lakes tends towards being a reddish-brown colour; this is due to the water absorbing most red and orange light less yellow, still less green and relatively little blue light (virtually identical response for salt and pure water). The "yellow substance" which acts as a strong filter absorbing much blue light,less green and very little yellow or red. Due to the strong filtering properties of yellow substance it over-rides the blue filter properties of water in rivers and lakes, thus the yellowish, reddish-brown colour results (Lythgoe, 1965). (This is summed up in fig. 12 from Wood & Lythgoe, 1976).

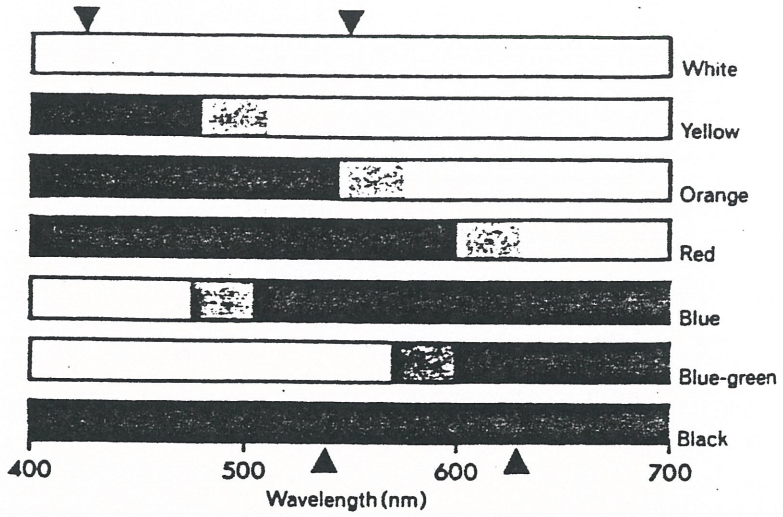


Fig. 12

The colours which result when certain regions of the spectrum are absorbed and not reflected (black areas); the stippled areas are those where the absorption varies rapidly with wavelength.

The triangular markers at the top and bottom of the diagram delimit the spectral region where 90 per cent of the daylight incident at the water's surface is absorbed at 80 m. in blue Jerlov type 11 ocean water (top markers) and yellow-green Jerlov type 9 coastal water (bottom markers). (After Woods And Lythgoe 1976)

Discolouration of the sea can also be caused by the presence of exceptionally dense swarms of phytoplankton and zooplankton blooms and red tides, and, very rarely, by airborne dust and sand.

The effects of each component of the seawater upon the incident light is summarized in Table. 1.

Also affecting the colour of sea water is the depth of water and substrate. In shallow waters with a reflecting bottom or observing propeller turbulence (bubbles) against a blue background, the water is given a greenish-blue colour due to the limited selective absorption by the water of these wavelengths (Jerlov, 1976).

J. Woods & J. Lythgoe (1976) discuss polarization of light underwater; they state that this is thought to be the result of the scattering of light rather than refraction from the surface. Most of the underwater polarization arises from scattering of the sun's rays by the water, and thus the plane of maximum polarization tends to be 90° to the sun's rays, therefore tilts during the day. Near to the surface in clear, deep

TABLE 1

COMPARISON OF INHERENT PROPERTIES (m^{-1}) [1]

Region	Wavelength (nm)	$c-c_w$ observed	b_p observed	a_p+b_p	a_p	Δa_p	a_p+a_y	$\Delta(a_p+a_y)$	a_y observed	Δa_y	Reference
Sargasso Sea	440	0.05	0.04				0.01				
Carribean Sea	655	0.06	0.06	0.06	0		0.00				
	440	0.09	0.06				0.03	0.03			Jerlov (1951)
Equator Central Pacific	440	0.09	0.05				0.04				
Romanche Deep	440	0.12	0.07				0.05				
Galapagos	655	0.11	0.07	0.11	0.04		0.04				
	440	0.24	0.08				0.16	0.12			
Off California	522	0.08	0.01				0.07				Tyler (1961a)
Off Peru (64 miles)	700	0.39		0.39					0		
	400	0.73		0.64		(0.25) *			0.09	0.09	
Galapagos	700	0.16		0.16					0		Burt (1958)
	400	0.25		0.21		(0.05 *			0.04	0.04	
Northwestern Galapagos	700	0.07		0.07					0		
	400	0.11		0.08		(0.01) *			0.03	0.03	
Continental slope	668	0.05									
	365	0.10		0.08		(0.03) *			0 0.02	0.02	Clarke and James (1939)
Bermuda	655	0.10		0.10							
	380	0.20		0.17		(0.07) *			0 0.03	0.03	Ivanoff et al. (1961)
Kattegat	655	0.23	0.15	0.23	0.08		0.08		0		
	380	0.54	0.16	0.44	0.27	0.19	0.38	0.30	0.11	0.11	
South Baltic Sea	655	0.27	0.20	0.27	0.07		0.07		0		Jerlov (1955a)
	380	1.15	0.21	0.49	0.28	0.21	0.96	0.89	0.68	0.68	
Bothnian Gulf	655	0.38	0.28	0.38	0.10		0.10		0		
	380	1.72	0.31	0.64	0.33	0.23	1.41	1.31	1.08	1.08	
Skagerrak	655										
	380					0.3		0.4		0.1	Malmberg (1964)
North Atlantic	665										
	420								0 0.03	0.03	
North Sea	665										
	420								0.01 0.10	0.09	Kalle (1961)
Baltic Sea	665										
	420								0.02 0.33	0.31	

[1] c = total attenuation coefficient; c_w = attenuation coefficient for water; b_p = scattering coefficient for particles; a_p = absorption coefficient for particles; a_y = absorption coefficient for yellow substance; Δ = wavelength selectivity; $c = c_w+b_p+a_p+a_y$.
* If $\Delta b = 0$.

(After Jerlov, 1968)

water there might be 60% polarization, this falling to 30% in deep water. The degree of polarization decreases with overcast sky, turbid water and also near the bottom (especially light coloured) due to upwards reflected light.

Polarization factor, $P = \frac{l_p}{l_n - l_p}$ where l_p is the linearly polarized fraction of incident light

l_n is the unpolarized fraction.

The human eye unaided is unable to detect polarization of light, but some arthropods and cephalopods are known to detect polarized light and its plane of polarization. Also in some fish it is thought that there is a birefringent adipose eyelid that may act as a polarizing filter. The advantage of being able to see polarized light is thought to be mainly in visibility, as most natural objects tend to reflect depolarized light from them, thus they have an increased visual range. So for polaroid vision nets that may be otherwise invisible, that is they have the same colour and reflectance to the background, will still be visible due to upsetting the plane polarization. (Blaxter, 1970; Hemmings & Lythgoe, 1967).

With the increased depth and monochromaticity of the light is an associated reduction in intensity due to absorption and scattering of the light, but with lower intensities bioluminance becomes significant and similarly at night time when it can have significant influence upon the effectiveness of fishing gear. (Hemmings, 1965)

Underwater Colour

The colour that an object appears underwater is dependent upon the wavelengths incident and those that are reflected rather than absorbed. Therefore black targets which absorb all wavelengths will appear black at all depths, but the objects which are red at the surface, appear

red because they absorb all other colours. But it is the red end of the spectrum that is most strongly absorbed by clear "blue" ocean water. So red targets would soon appear black with increasing depth as all the required wavelengths are absorbed.

Any surface that reflects all wavelengths of light equally looks grey (white), but if one wavelength is reflected more strongly than others then this is the colour it appears. Similarly, if more than one colour is predominant the object colour is the result of the mixture if all required wavelengths available in incident light.

In the same way a blue object in green water will appear black, whilst a blue-green object in ocean water and a yellow object in yellow-green water will retain their colours and resemble the colours of an object that appears white or pale grey on the surface. Also, being the same colour as that of the most penetrating light they will retain their colour to considerable depths (Woods & Lythgoe, 1976, after Lythgoe 1969). As colour vision in fishes and man are thought to be essentially similar, although there are differences in detail; qualitative appraisals, such as the viewing of nets in situ by man, is advantageous as it is thought to apply equally well to fish and man. (Lythgoe, 1965; Tansley, 1965). But in using man to observe the "visibility of colours" one should understand the mechanisms by which it is done, these being (a) colour recognition, (b) colour conspicuousness, (c) colour differences.

(a) <u>Colour recognition</u>

A diver sees objects both on the surface and at depth by the colours that they emit. Thus blood,which has a reflectance maximum in the red with a lesser peak in the green will, at depth, appear green due to the long wavelength red light having been absorbed by the water.

With fluorescent colours which absorb high energy short wavelengths and re-emit in the low energy long wavelengths, i.e. green, orange or red. Therefore the red and orange will stand out well against the blue green water backgrounds, and being that the colours depend more on fluorescence rather than reflectance their apparent colours remain true at all depths. But the eye has a remarkable ability to adapt to the different colour of ambient light. So when a yellow object on the surface is seen at depth in blue water it will be recognised as being yellow although in fact it is reflecting mainly in the green wave bands. This phenomenon of "colour adaption" has received little attention in the underwater context. According to Woods & Lythgoe (1976) the only work done in this field is by Kinney & Cooper in 1967 under simulated underwater conditions. The mechanism appears to be that the eye when presented with a change of ambient light, i.e. to blue, reduces its sensitivity to that colour, and then other colours, i.e. red, than can be detected to considerably lower intensities than would have been expected. This effect is possibly enhanced by the eye in man having a lens that becomes progressively yellower with age. (Woods & Lythgoe, 1976, after Wyszecki & Stiles, 1967). Thus it acts as a yellow filter. Similar optical filters have been found in fish either in the lens, the cornea or as coloured oil droplets in the cones, and it is possible that this adaption occurs in fish.

This change in sensitivity in the 3 visual pigments of day vision (photopic) in eye is thought to take less than 5 minutes. The maximum absorption of the 3 visual pigments are at about 440, 540, 567 nm. This gives both colour and brightness detection with day (cone) mediated vision, with greatest sensitivity being for yellow-green light in the daytime, though the range of sensitivity cover all "visible" light.

It should be noted that in all but deep water fishes their peak sensitivity is displaced to one side of the peak intensity of the light in the water, this would give better visual contrast (Lythgoe, 1965).

(b) Conspicuous colours

Any colour which contrasts strongly with the background will generally be conspicuous. In general underwater objects tend to approach the same colour as the depth or viewing range increases due to different rates of selective absorption by the water of the light of different wavelengths and are distinguished by relative brightness contrast rather than colour contrast. This results from selective adsorption of light as it propagates through the water as discussed earlier, but some colours, e.g. deep blue and yellow in clear blue water or red and in yellow-green water, do tend to contrast strongly in colour. Similarly fluorescent colours are always conspicuous. Also fluorescent animals and plants (red algae) are equally conspicuous as they are unlikely to be viewed against fluorescent backgrounds and therefore tend to have high contrast. Note: Fluorescent animals are only found in the sea. Although some fluorescent matter is produced as a byproduct of "yellow substance" formation especially in fresh water.

(c) Liminal colour differences

There is a limit to the range at which 2 radiances can be distinguished by their colours. This is the result of apparent contrast between the 2 objects, this being reduced with range due to attenuation.

Vision in Man

In man there exists 2 visual systems, one adapted for seeing in dim light (scotopic), the other for vision in daylight (photopic). Once light reaches the rods and cones it is absorbed by their visual pigments; these being chromoproteins which have similarly shaped, single peak

absorption curves which are spread through the spectrum.

The night vision system works with the rods, these contain a single visual pigment with maximum absorption at 502 nm (blue-green) although the response ranges from 400 to 650 nm. But containing only one visual pigment it is incapable of detecting different colours, only differences in brightness are detected. (Blaxter,1970)

Day vision only occurs above a threshold light intensity between 0.4×10^{-4} and 0.4×10^{-2} $\mu W\ cm^{-2}\ s^{-1}$ (3/4 moon). It is mediated by cones which are of 3 types, each containing a visual pigment of maximum absorption at about 440, 540, 567 nm. Having these 3 pigments it is capable of detecting both colour and brightness differences. The range of detection is much larger from 400 to 700 nm with a peak at about 555 nm (yellow-green light).

Also above 650 nm only photopic vision exists.

The transfer from day to night vision in the eye takes at least 25 minutes this being dependent upon the previous intensity of light experienced. Once vision has been completely transferred to scoptic vision it gives 10^9 fold increase in sensitivity for seeing objects. The reverse transfer from night to day vision is much quicker.

To enhance a diver's vision in poor light conditions the dark adaption stage can be completed using red perspex (ICI 400) in place of the glass in the face mask. Then when at depth where there is only sufficient light for photopic vision change back to a clear glass face mask and the benefits of night adapted vision in the low light levels is obtained. This could be valuable in using divers in observation of fishing gear both in poor light due to depth and turbidity of the water or in twilight/night conditions (Hemmings & Lythgoe, 1964).

In fish they tend to have even denser masses of rods. This giving deep sea fish a further 10 to 100 times more sensitivity to dim light than in man (Woods & Lythgoe, 1976).

According to Jerlov, 1976, colour vision (cones) are most frequent in the central part of the retina and the low intensity monochrome vision rods are located around the sides. The 3 types of cone gives 3 independent colours (red, green, blue) mixed responses from which give the impression of any colour seen. So for my nets dyed grey, brown, red, yellow, black, green and blue plus an uncoloured white net the black net will appear black due to not triggering any cone cells. Light from the blue net when seen will trigger the blue sensitive cones, the degree of response determining the brightness. Light from a yellow net is absorbed strongly by the green cone, slightly less strongly by the blue and only weakly by the red to give a combined response equivalent to that shade of yellow.

Vision in fishes

The eye of a fish is covered with an adipose eyelid, the extent of this is variable, ranging from total in elopids, engraulids, stromateids and polynemids; to having an eleptical opening over the pupil separating the anterior and posterior halves as is found in dupeiods, magilids, corongids and scombrids. In salmonids only a small posterior part of the eyelid is covered. The purpose of these eyelids was originally thought to be for streamlining, but it is now known that they are birefringent (Blaxter, 1970).

Lythgoe & Hemmings (1967) and Woods & Lythgoe (1976), gave the presence of this as giving the possible potential for seeing polarized light. This could give orientation stimuli, improve visual range and improve the contrast between object and background and aid seeing other members of fish in the school.

The movement of the pupil is found in elasmobrachs and some teleosts, namely Anguilla, Lophius and Uranoscopus. The dilation of the pupil appears to be the direct effect of light in Anguilla and some selachians. In other teleosts pupil contractions are controlled by sympathetic and dilation by parasympathetic nervous systems. The contraction in Anguilla has a peak reaction at 500 nm, this being the same as the maximum absorption (λ max) of the visual pigment rhodopsin (Nicol, 1963).

The retina consists of 2 types of light receptors, cones and rods. These are variable in size, numbers, density, distribution and the type of visual cells. The density and distribution of which may be the result of the habitat in which they live.

In some fish the distribution and density of the retina gives a visual axis, suited to their mode of life and habitat, i.e. bottom feeders for example Sea bream Sporus have an axis in the anterior-downward (lower-fore) direction; sail fish Istrophorus has the axis in an anterior-horizontal (forwards) direction; and pelagic feeders, i.e. horse mackerel Trachurus which take food from below have a visual axis in the anterior-upward (upper forward) direction (Blaxter, 1970).

The rods in the retina are responsible for low light intensity scotopic vision. Summation of rods all triggering the same bipolar neuron results in greater sensitivity as several receptors reinforce each other, but this is at the cost of acuity. Cones work at higher light intensities giving photopic vision. With cones there tends to be less summation thus giving higher acuity, this is further enhanced by higher density of cones.

The acuity or resolving power is the ability to discriminate between 2 objects (or parallel lines). To avoid the problem of distance the

acuity is given as the angle subtended at the eye (in minutes) when the objects are just separable. Thus high acuity is when the separation of the angle of targets is small. It is assumed that 2 objects are resolvable when there is an unstimulated visual cell (or group of cells where summation exists) between 2 stimulated cells. So summation tends to reduce acuity to gain sensitivity.

$$\text{Sin } \alpha = \frac{1}{F} \left[\frac{0.1\ (1 + 0.25)}{n} \quad x\ 2 \right]$$

where α is the minimum separable angle, F is focal length of the lens, 0.25 is the degree of shrinkage and n is the number of cones in 0.01 nm^2. The value of n varies greatly from different parts of the retina being greatest in the pure cone temporalis and least in the peripheral retina.

The values of range from 2-4' for some pelagic fish and 6-9' for other species.

The acuity increases with brightness, this being greatest at dark-light adaption ranges. Also acuity increases with age due to focal length (F) increasing, although cone density (n) reduces with age though at a slower rate (Blaxter, 1970).

Also in fish, like man they appear to find that a white object when viewed against a black background appears larger than a black object when viewed against a white background. So for maximum acuity the net should be darker than the background rather than lighter (Baronov, 1924).

In many species the retina consists of both rods and cones, thus having scotopic (achromatic) and photopic (colour vision); each working at different peak sensitivities (the shift from one to the other is

called the Parkinje Shift).

Some elasmobranchs and deep sea fish (and sturgeon (Protasov, 1970)) appear to have only rods in the retina. Wrasse have a pure cone retina (Blaxter, 1970). Many larval fish stages have a pure-cone retina, for example Pacific salmon Oncorhynchus spp, herring Clupea harengus and plaice Pleuronectes platessa (Blaxter, 1970).

To give improved vision many fish have binocular vision of 20 to 40° overlap, this is enhanced by sighting grooves in the head and lens that protrude. This also gives about 300° field of vision in some fish. By having binocular vision it gives a degree of appreciation of distance. This is also enhanced by the movement of the pupil and of the lens to focus on objects (Tansley, 1965).

This is also discussed in relation to visual ranges of fish in Monteifel et al (1967), Blaxter (1970) and Protasov (1970). Protasov (1970) gave visual ranges of up to 3 metres for stationary objects but up to 20 metres for large moving objects or shadows - these initiating flight reactions.

In Elasnobrachs and deep sea fish to improve the sensitivity further the number of rods present is high though this means that they are smaller. Some species have only rods present. Many elasmobranchs (and engraulids) have a tapetum present; this is a layer of reflecting guanine crystals in the choroid behind the retina. These crystals reflect only along the path of incident light thus restimulating the visual cells increasing its response and sensitivity. Due to no stray reflections there is no loss of acuity. Another advantage is that dark adaption is accelerated due to the lower density of rods required with tapetal reflectors. To protect the tapetum from high light intensities there is a movement of tapetal pigment. This

aggregates periphally in darkness and disperses over the guanine reflecting layer in higher light intensities. The threshold intensity is unknown but the mechanism is thought to take about 2 hours. Examples of elasmobranchs with tapetal pigment migration include Squalus, Mustelus and to a modified extent in Scyborhinus.

The distance by which the tapetum extends vision underwater relative to a retina with a tapetum being absent is discussed by E.S. Zyznar (1975). If the increase in retinal illumination due to the presence of the tapetum is donated by a factor, t, and beam attenuation coefficienc, c, then the additional visual range ΔD is

$$\Delta D = \frac{2.3 \log t}{c}$$

t tends to be less than 1.5 and ΔD gained is up to several metres for the normal range of attenuations found in natural waters.

Similar response occur in teleosts where there is a duplex retina (rods and cones). A retinal pigment covers the rods while the eye is operating in photopic (light-adapted) conditions. In low light intensities the pigment withdraws exposing the rods for dark adapted vision (Nicol, 1963).

This response has been shown in most teleosts but it does not occur in teleost larvae or pure-rod eyes as in elasmobranchs and in deep sea fish (Blaxter, 1970).

The threshold for this dark adaption is between 4 and 0.4 $\mu W\ cm^{-2}\ s^{-1}$ for smelt and 0.4×10^{-3} - 0.4×10^{-4} $\mu W\ cm^{-2}\ s^{-1}$ for carp and roach. Blaxter, 1970). The speed of transfer from photopic to scotopic vision (dark adaption) in fishes takes about 30 minutes with visual threshold increasing from 0.4×10^{-1} - 0.4×10^{-2} to 0.4×10^{-5} - 0.4×10^{-7} $\mu W\ cm^{-2}\ s^{-1}$. The reverse light adaption takes only 10 to 30 seconds (Monteifel et al, 1967; Blaxter, 1970; & Protasov, 1970).

Brightness discrimination is defined by $\Delta I/I$ (Weber's fraction) where ΔI is increment of intensity just distinguishable and I is the ambient intensity. This usually falls with increasing I. Thus a smaller percentage change $\Delta I/I$ is detectable at high light intensities than at lower intensities. Weber's Law that $\Delta I/I$ is a constant is only actually true over narrow ranges of intensity I. (Blaxter, 1970, 1975; Lythgoe, 1975).

The range of values of $\Delta I/I$ vary from 0.06% to over 100% depending upon species and level of illumination with values of 5% to 30% being most common (Protasov, 1970). Some species are very insensitive, for instance dog fish Mustelus where $\Delta I/I = 1400$ and eel Anguilla where $\Delta I/I = 540$. This variation of brightness discrimination found here must have some influence upon apparent contrast of objects, i.e. nets in different light intensities especially near the surface during daylight where ambient intensity can be relatively high.

Another important factor relating to this response is that pelagic fish are thought to follow vertical migration diurnally in response to levels of illumination. That is changing depth to keep $\Delta I/I$ at a constant level. So if the Weber's fraction for a fish is 10% then in inshore coastal waters it would have to move less than 1 m and only to 2 to 3 metres in oceanic water to detect 10% change in ambient illumination. There exists uncertainty as to whether a fish could detect this gradual change in intensity as it swims up especially in clear oceanic waters (Blaxter, 1970, 1975). This phenomenon of the depth of pelagic fish shoals being related to ambient light intensity which is in turn a function of incident illumination and turbidity (defined by turbidity coefficient k), could be used to set drift nets at an appropriate depth to catch fish during the day as well as at night by raising the net to keep it at the illumination level followed by the species sought after.

For fishes to have colour vision comparable to man it requires the presence of cones which react to 3 primary colours and this combination of these will give any colour in the visible range (Blaxter, 1970). Most fish have some degree of colour vision (possibly all) (Tansley, 1965; Blaxter 1970, 1975) and in mullet Mugil cephalus, carp Cyprinus carpio and goldfish Crassius auratus it is very well developed (Blaxter, 1970, 1978; De Reuck and Knight, 1965; Tansley, 1965).

The only elasmobranch shown to have colour vision is the sting ray Dasgatis akajei (Blaxter 1970, 1975). The lemon shark Negaprion brevirostris has been found to have the components of colour vision, (Purkinje shift) rods and cones with appropriate pigments (Gruber, 1975).

The presence of colour vision is usually tested experimentally either by training a fish to select a certain colour when presented with a range of colours of the same brightness, or by selecting a coloured container from a series of grey ones covering a range of brightnesses. In the first case the brightness of colours is dependent upon the visual sensitivity to that colour for the light adapted eye. Tansley (1965) has done such experiments with minnows (Phoxinus laevis) and sticklebacks (Gasterosteus aculeatus). The former shows well developed trichromatic vision comparable to man. Nicol (1967) discusses research into colour vision of blennies (Blennius pholis) and states that they have a wide range of colour vision, could discriminate colours, i.e. blue, green, and red from grey but could not discriminate between varying intensities of grey.

Other research has shown the minnow (Phoxinus laevis), the ide (Idus), the bitterling (Rhodeus) and Tench (Tinca) all have the ability to discriminate between colours (20 in the case of the minnow) in the visible spectrum. Though colour vision is lost when the intensity of

adaption drops below 0.1 to 0.004 $\mu W\ cm^{-2}\ s^{-1}$ in general no teleost has ever been shown not to have colour vision (Blaxter, 1970, 1975) and it is always trichromatic (Tansley, 1965). A possible exception to this is the sturgeon (Acipenser spp.) according to histological evidence (Protasov, 1970; Denton & Nicol, 1965).

The nature of visual pigments has long been thought to depend upon the environment in which the fish lives. In 1936 two separate researchers put forward the hypothesis that deep water fish living at depth where mainly blue light (470–480 nm) penetrates would have visual pigments especially sensitive to these wavelengths. These hypotheses were later supported by research in the 1950's (Lythgoe, 1965; Munz, 1975).

On the basis of what was found for deep sea fish it was initially suggested that other fish living in shallower waters would show similar correlations between visual pigment sensitivity and light spectrum available in the water, but this was found not to be the case. With the visual pigments peak absorption (λ max) being shifted from that of peak water transmission (λ min) (Blaxter, 1970; Lythgoe, 1965; Munz, 1975; De Reuck & Knight, 1965). Much of the research into visual pitments has been done on rods due to difficulties in extracting cone pigment (Blaxter 1970).

From extraction & photochemical studies of rod pigments there appears to be 2 main groups of pigments; (i) rhodopsins with a λ max around 500 nm being related to vitamin A and found in elasmobranchs and mainly marine teleosts such as sword fish, sea bass, sand flounder, herring, haddock and whiting (ii) porphyropsins with a λ max around 522 nm, related to vitamin A_2 is found in freshwater species such as catfish, perch, carp, goldfish and blue gills. This picture is further complicated by both A_1 and A_2 based pigments being present

in fresh water and anadromous and catadromous species (Blaxter, 1970; Lythgoe, 1965; Manz, 1975). In anadromous species, e.g. salmon, there is a rise in porphyropsin during spawning migrations to fresh water and in the anadromous perch (Morore ambicans) the pigment is pure porphyropsin.

In catadromous species, e.g. eel (Anguilla anguilla) rhodopsin predominates in freshwater but on migration to the sea for spawning the pigment λ max changes towards the blue end of the spectrum by about 33 nm. The new pigment chrysopsins (visual golds) have a λ max at about 485 nm, similar to that of elasmobranchs deep sea teleost fish (Blaxter, 1970; Nicol, 1967).

Fish can also change the λ max of their visual pigment according to the environment in which they live. The rudd (Scardinius erythrophthalmus) if kept in the dark distribute the pigment in the eye to improve night vision (Tansley, 1965). Also with increasing day length the proportion of vitamin A_1 based pigment increases so the rudd becomes relatively more sensitive to short wavelengths during the summer. Also the dorsal part of the retina has more A_1 based pigment thus it is more sensitive to short wavelength when looking downwards. As the λ max of the pigments shift towards the shorter wavelengths in summer the water mass due to higher productivity shifts its λ min towards longer wavelengths, and upwelling light tends to be redder than the downwelling light. By the earlier hypothesis it appears that the rudd (and many other species) are not adapted for sensitivity having λ max displaced from λ min of the water (Munz, 1975).

Lythgoe (1965) was the first to review the previous view that a fish had visual pigments with λ max similar to λ min of the environment. This though true for deep water fish has been found not to be the case

for Mediterranean, coastal or estuarine fish, see table 2 and figure 13

Table 2

Characteristics of visual pigments in different environments (After LYTHGOE, 1965)

Area	λ max pigments (nm)	λ min water (nm)
Mediterranean	493–506	465
Deep sea	478–490	485
Coastal	494–501	530
Estuarine	504–512	590

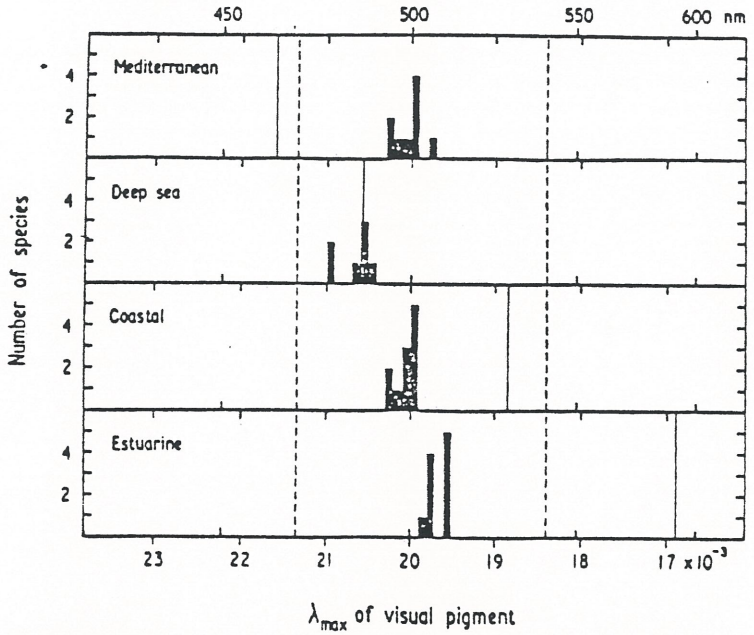


Fig. 13 The distribution of visual pigments in fishes from different photic environments. The histograms give a plot of pigment λ_{max} in wave numbers and nanometers against frequency of occurrence (number of species yielding a single visual pigment). The vertical line represents a reasonable value for the λ_{min} of each water type. The interrupted lines delimit the known range of fish visual pigments, and the extent of the abscissa the known range of visual pigments from all sources.
(After Lythgoe, 1965)

An extensive review of the pigment types present, their ratio and comments upon the environment in which the fish lives is given by Ali and Wagner (1975). These also include fresh water species which have pigment with λ max of about 520–530 nm. Where λ min of the water shifts towards yellow due to the presence of yellowish humic acids (yellow substance).

The probable reason for the visual pigment λ max being offset from λ min of the water areas (with exception of deep sea fish) is to enhance contrast between object and background but at the expense of sensitivity. This is due to the differences in path lengths. The background light having travelled further has undergone more absorption at higher (and lower) wavelengths thus has a slightly different spectral distribution than light coming directly off the object. If λ max of the eye coincides with λ min of the water the difference in energy and thus contrast of object and background will be small. If offset the energy difference is far larger, therefore relative contrast will be greater (Blaxter, 1970; Lythgoe, 1965). See fig. 14 and fig. 15.

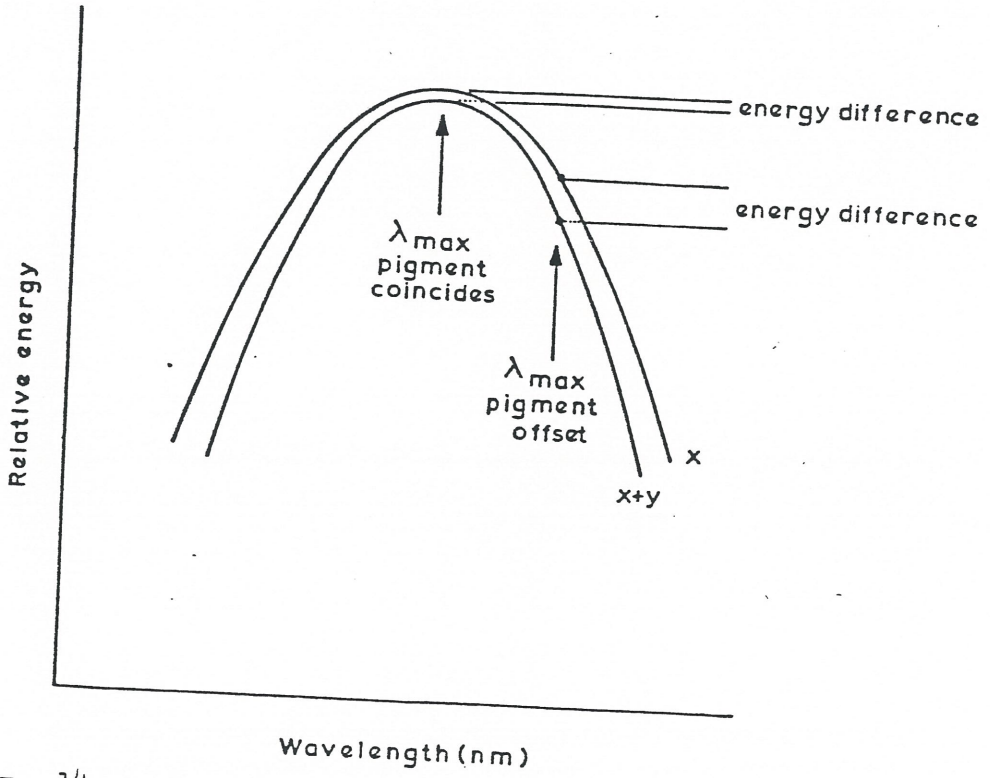


Fig. 14 : Relative energy of different wavelengths at depth x and depth $x+y$. Energy differences between light reflected from the background (path length from surface $x+y$) and from a nearby object (path length x) are shown where maximum sensitivity (λ_{max}) coincides with the λ_{min} of the water and where it is offset. Note the contrast between background and object will be greater where the pigment is offset. (After Blaxter, 1970)

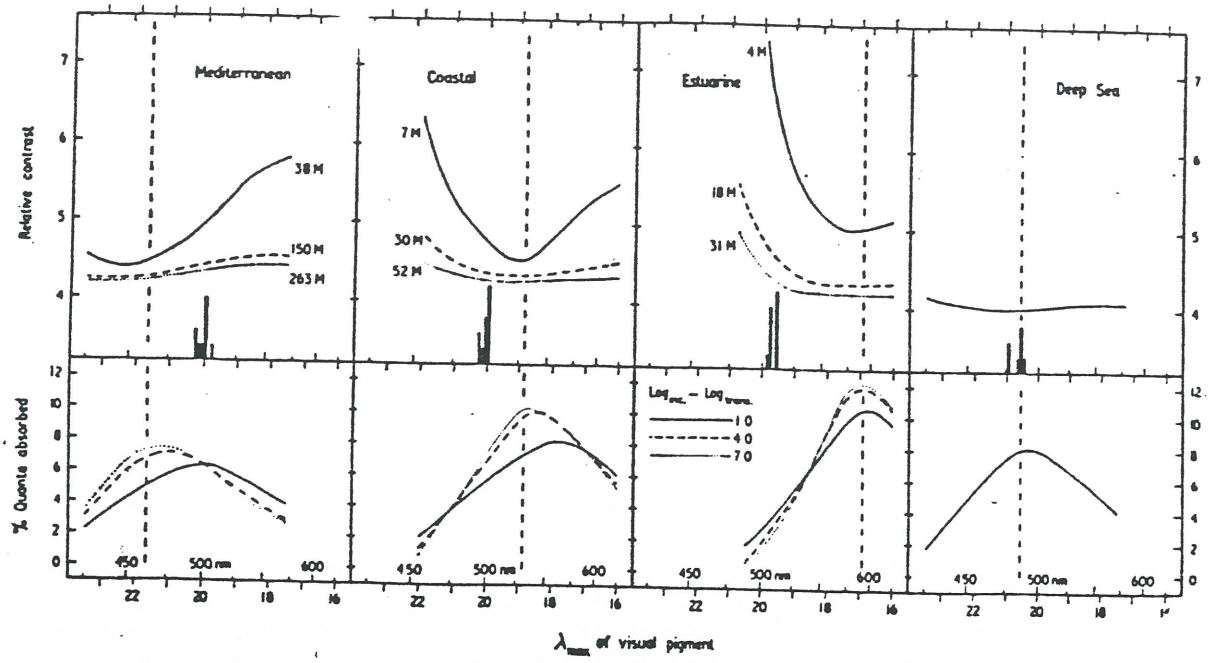


Fig. 15 The advantage in sensitivity and contrast perception conferred by rhodopsins of varying λ_{max} in four types of water and at three optical depths. The histogram plots, explained in Fig. 2, represent the λ_{max} of the visual pigments of fishes found in each environment. The vertical interrupted lines represent the λ_{min} of each water type. The curves are calculated for visual pigment optical density 0·1 and for 4800° K daylight.

(After Lythgoe, 1965)

For any visual pigment where λ max is offset from the maximum intensity of incident light will absorb fewer quanta of energy from both background and object, but the reduction of quanta absorbed from the background will be greater for background light; therefore the difference in quanta from each will be greater. See fig. 14.

This means that the object light becomes brighter relative to the background light. So an object already brighter than its water background becomes easier to see, but any object darker than the background will become less visible or invisible if its contrast falls below the visual threshold (Lythgoe, 1965). This fact has an important effect upon the designation of an invisible net. To be invisible it must be slightly darker than the water at that depth. This requires a net where colour and intensity emitted is the same as the background light against which it is viewed or the net must act as a perfect mirror or be totally clear (as is approached by monofilament).

Values of contrast detectable as a percentage for daylight adapted fish range from 0.01 for capelin, 1.00 for pollack and cod through to 7-10 for plaice and thorny skate and 10-12 for wolf fish, with % contrast sensitivity being greatest in twilight for pollack (Protasov, 1970).

The visual pigments in cones (for colour-scoptic vision) has been less well studied. Most theories for colour vision require 3 pigments (usually one in each cone) absorbing in blue or violet, green and red (Blaxter, 1970). In gold fish (Carassius auratus) the maxima of pigment absorption are at about 455 nm for blue, 530-35 nm for green and 625 nm for red (De Reuck & Knight, 1965; Stell, 1975). De Reuck & Knight (1965) gives the equivalent maxima for man as being 445 nm, 535 nm and 570 nm.

The three pigments in cone vision appear from their absorption spectra to be based on vitamin A_1 - rhodopsins (de Reuck & Knight, 1965). But in pure core vision, i.e. wrasse, the pigment is based purely upon vitamin A_2 - porphyropsin. Many fish tend to have intermediate pigments in their cones which have both pigments (Ali & Wagner, 1975; Nicol, 1967).

The spectral sensitivity of the eye is related to the spectral sensitivities of the pigments involved. The sensitivity to different wavelengths is usually similarly related though can be increased by denser pigments concentration or summation of those rods/cones with the required pigment. So most fish have a rod mediated spectral sensitivity - photopic vision and a cone mediated spectral sensitivity - scopotic vision. Each has a wavelength of peak sensitivity. These 2 peak sensitivities for photopic and scoptic vision occur at different wavelengths and the change from one to the other is called the Purkinje shift (Protasov, 1970).

In most elasmobranchs there is only pure rod vision and thus no Purkinje shift. In low light intensities (photopic vision) the eye is most sensitive to blue part of the spectrum in bright light (scopotic vision) with pure blue light the response curve is similar to that of photopic twilight vision although according to the Purkinje shift the sensitivity should have moved towards the red part of the spectrum. (Blaxter, 1970). The explanation of the Purkinje shift is not known but Dartnall (1975) reports the possibility that it provides a mechanism for distinguishing brightness contrast while in scopotic (colour) vision conditions.

The Purkinje shift in both man and fish is not instantaneous, taking only 10 seconds for dark to light adaption but up to several hours for the reverse light to dark adaption depending upon adapted illumination levels. This occurs when the illumination falls below the threshold for scopotic vision. Once dark adapted the sensitivity increases by about 10 million times but in the transitional period sensitivity is much reduced. The dark adaption time for man is approximately the same as that of fish (Protasov, 1970).

Apart from the changes in peak sensitivity (Purkinje shift) between photopic and scotopic vision there is also a change in the spectral range of each. For example with the mullet (Mugil cephalus) when photopic adapted has a spectral range from about 450 to 640 nm, when scopotic adapted this shifts to 480 to 680 nm. Thus the shorter wavelengths are no longer detected and while longer (red) wavelength become detectable. (See fig. 16)

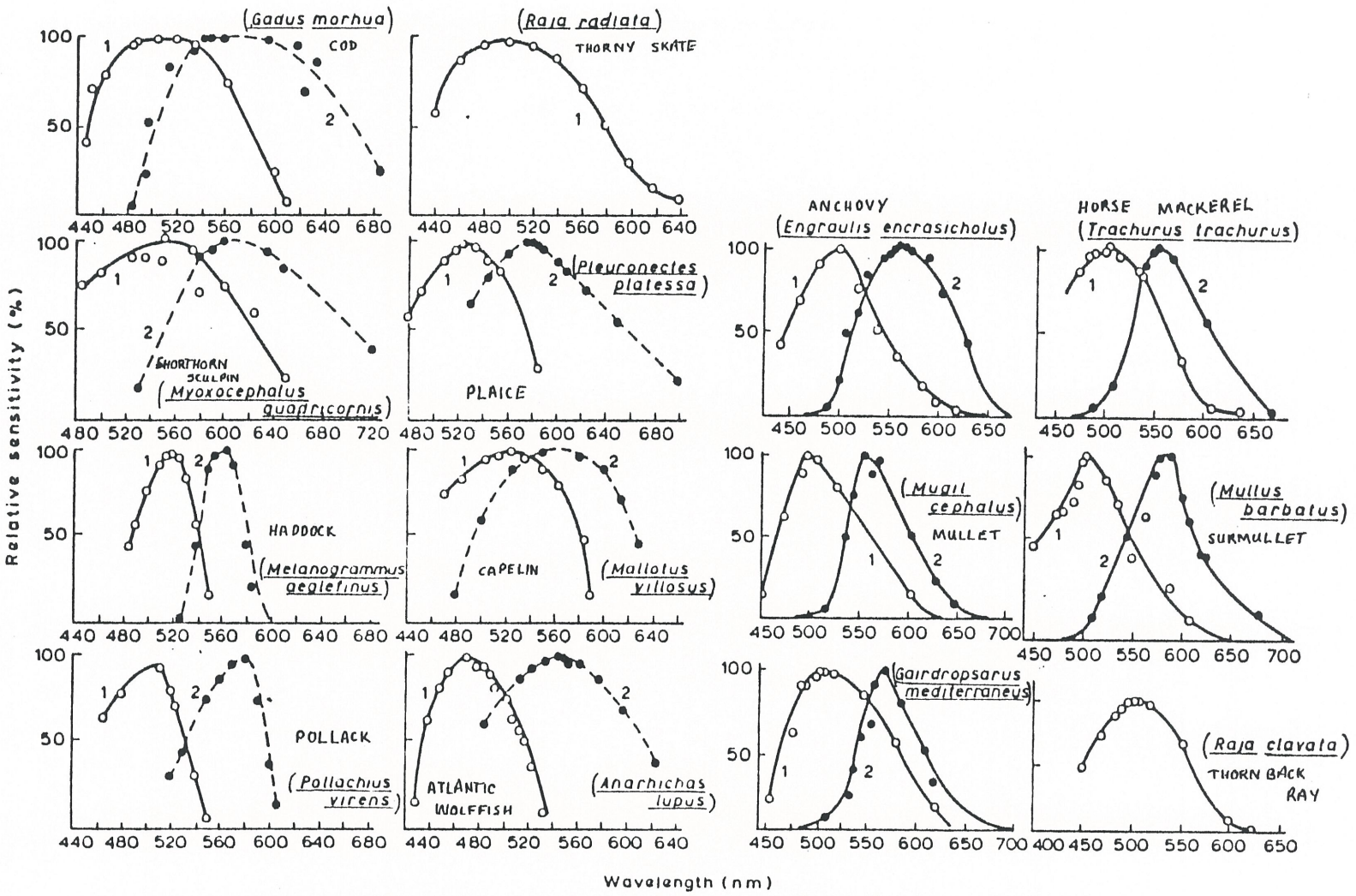


Fig. 16 Spectral sensitivity of various species obtained by ERG. (After Protasov, 1964; redrawn.)

Adaptive colouration and camouflage in fish

Fish by nature of their colouration and scales tend to be inconspicuous in their natural environment. This has probably evolved to give protection from predators by camouflage with the background. Due to the nature of propagation of light underwater, a fish to be inconspicuous must be dark coloured on top to match the less intense upwelling light when viewed from above and similarly lightly coloured (white) underneath so as to match the downwelling light when viewed from below. When viewed horizontally intermediate colouration is required to match the horizontal illumination against which it is viewed.

Demersal species, especially flatfish, i.e. plaice, use chromatophores in their dorsal surface to imitate the substrate on which they lay. Similarly elasmobranchs tend to be simply shaded to match the substrate while the under sides of both tend to be creamy white due to the absence of chromatophores. (Blaxter, 1970).

In general shallow water species show the widest range of colouration and these change both minute to minute and over longer periods. The simplest way of altering the brightness is by changing the ratio of melanin to guanine to suit the amount of reflected light from the surroundings. In some reef, weed or fresh water living species they tend to have vertical bars on their sides so as to merge with the environment but when moving fast the vertical bars in some species tend to change to longitudinal stripes which possibly give the appearance of moving faster thus deterring predators. This behaviour is seen with many reef species (Hemmings, 1965).

An example of the range of colouration between dorsal and ventral surfaces and its change with environment is found in the Mediterranean wrasse (Coris julis). The dorsal surface is greenish brown and the

ventral surface creamy white; along the flanks rather than the two colours blending together they form a distinct line along the flank.

These fish live between 0 and 40 metre depth but the back colouration when viewed at the surface in white light range from greenish brown at the surface to bright reddish-brown for the deepest fish. Thus there appears to be compensation for the selective absorption of light of different wavelengths by individuals living at different depths (Hemmings, 1965). This suggests that the colour of a net that would be least visible would also vary with depth.

F.I. Baronov (1924) in experiments with different coloured nets in freshwater lakes found that an olive-green net caught by far the most fish and on closer observation he found that the olive-green net perfectly matched the colouration of the backs of the perch being caught. He also found that this varied with the depth from where the fish came. He concluded that the best colouration of the net is that of the back of the fish being sought from the depth to be fished. I.V. Nikonorov (1973) restates Baronov's hypothesis that the best coloured net matches the back of the fish in colour.

In contrast pelagic fish tend to generally have carangid shape and be active swimmers. The back usually has well developed countershading in blue or green/blue on the dorsal surface with silvery flanks (Hemmings, 1965).

Denton and Nicol (1966) worked on the silvery sides of Alburnus alburnus, Trachurus trachurus, Clupea harengus and some other species. They discovered 2 kinds of reflecting layers (1) an argenteum containing long thin guanine crystals whose reflecting surfaces are parallel to the fishes surface, i.e. mackerel, (2) a layer of crystals on the inner surface of scales, or in the subdermis where orientation of the crystals

varies so as to keep all the reflecting layers vertical, i.e. herring. This gives the same effect as a mirror, being unaffected by the shape of the fish. Provided that there is no change in illumination with zenith angle then such a mirror surface will, if viewed at any angle reflect light of the same quality and quantity as would be seen if the mirror was absent therefore such a mirror surface would blend in totally with the background, i.e. inherent contrast equals zero(Blaxter, 1970; Denton & Nichol, 1966; Hemmings, 1965; Lythgoe, 1965). Therefore effective camouflage of pelagic fish will be affected by both the efficiency with which they resemble a mirror and also the depth at which they swim due to there being quite strong directional illumination from the sun in shallow depth, this depending upon scattering and elevation of the sun (Hemmings 1965).

With such fish the vertical mirror is replaced by a series of small reflectors (argenteum layers) all vertically orientated. To avoid stray reflections of downwelling light from the dorsal surface if viewed from above the back is generally darkly coloured. The ventral surface is usually keel like; this might tend to reduce the silhouette when viewed from directly below (Blaxter, 1970).

The presence of these reflecting layers may have an influence in schooling behaviour of these fish. Such pelagic fish are generally schooling fish but due to near perfect reflection they have low visibility when swimming in a straight line, but only sudden movement for example if one fish breaks out of the school or is frightened, the change in orientation of the fish induces a flash of reflected toplight thus making it conspicuous for the school to keep together (Lythgoe, 1965; Hemmings, 1965).

Blaxter (1970) reports that in earlier work by Denton & Lythgoe in

1965 they found that the amount of polarized light reflected off Alburnus alburnus was surprisingly small. This is due to the presence of birefringent eyelids in many fish providing it does act as an analyser for polarized light, could aid seeing other fish and thus maintain shoaling (Lythgoe & Hemmings, 1967).

Pelagic fish tend to migrate to the surface at dusk and return to deeper water at dawn (Blaxter, 1970, 1975). If the illumination falls below 0.1 mc the shoal tends to break up, but with the dawn comes less homogeneously distributed light and reforming of schools is aided by the poorer camouflage (Blaxter, 1970).

A further mechanism employed by fish, especially fish larvae is to have transparent (e.g. the cornea and the lens of the vertebrate eye) and translucent (e.g. muscles and nerve fibres of squid) tissues. Any animal made of such tissues will be hard to see in the diffuse light found underwater.

Any internal organs, i.e. digestive tract, red muscle, kidneys and livers of fish and ink sacs of cephalopods which cannot be translucent are coloured as if individual fish; silvery on the sides and dark on top. Examples of these are the eyes and digestive tract of fish larvae, i.e. plaice and sole. The eyes, digestive tract and ink sac of the otherwise translucent squid. The sand smelt (Atherina presbyter) which has silvered sides and darker tops to the visceral organs and the two bands of red muscle, also the sand smelt does have some partial silvering on the lower flank though when viewed from most angles appears translucent. (Denton & Nicol, 1966). This mechanism of reducing ones visibility by being translucent is the same principle as monofilament twines, as used in some nets. Monofilament twines are always less visible than multifilament twines due to their lower contrast. This is often reflected in higher catches from monofilament nets. (Angelsen & Huse, 1979; Blaxter & Parrish, 1965; Von Brandt, 1972; Larkins, 1963,64;

Molin, 1957; Steinberg, 1963; Tran-Van-Tri and Ha-Khac-Chu, 1963).

Propagation of Light Underwater

The passage of image forming light in the sea is effected by two processes -

(1) asborption - conversion of light into heat energy

(2) scattering - change in direction of travel of light energy due to scatterers in the water.

The two processes together are called (total) attenuation.

(1) Absorption:-

This is signified either by:-

i) Absorptance (A) which is the ratio of the radiant flux lost by absorption to the incident radiant flux or the ratio of light intensities (I), (see Fig. 17)

where $A = \frac{F_a}{F_o} = \frac{F_o - F_{\Delta L}}{F_o}$ (similarly $A = \frac{I_A}{I_o} = \frac{I_o - I_{\Delta L}}{I_o}$)

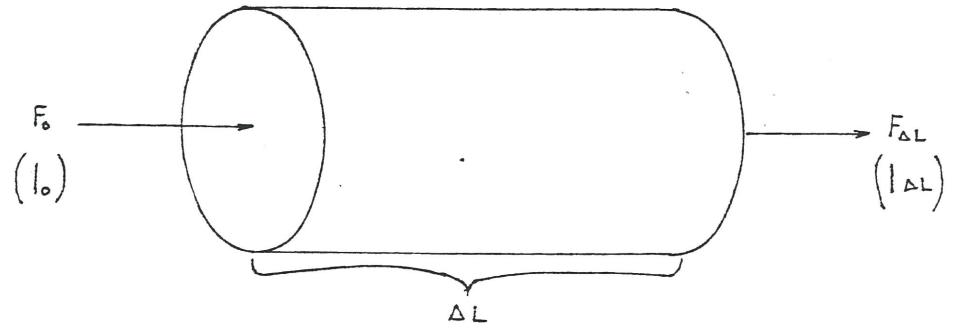


Fig. 17 Absorptance

ii) Absorption coefficient (a) this is the rate of absorptance per unit length

where $a = \frac{-\Delta A}{\Delta L} = \frac{-\Delta F_a}{F_o \Delta_L}$ (in units of metre^{-1})

This is assuming that the sea is homogeneous. This is generally true in the horizontal plane, but not usually so vertically, although the change in a with depth can be considered insignificant as far as optical ranges are concerned. Assuming an homogeneous medium $aL = -\ln(1-A)$.

The absorption rate is also wavelength dependent, being greatest in the infra red end of the visible spectrum and to a lesser extent in the ultra violet end. (see Fig. 18)

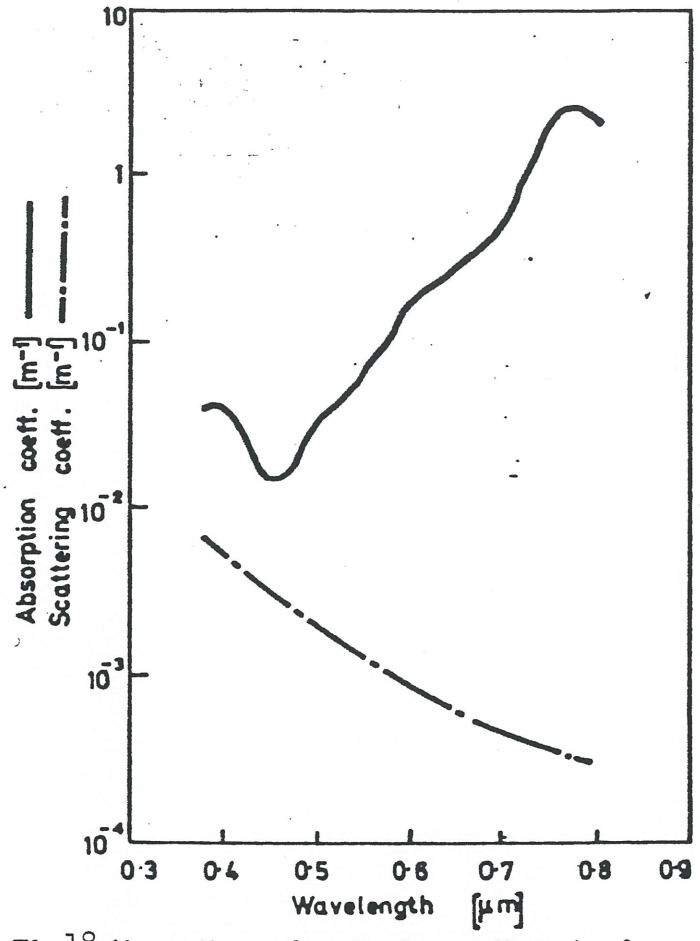


Fig.18 Absorption and scattering coefficients of pure water as a function of wavelength (visible region) (After Gazey, 1970)

The absorption coefficient (a) is related to transmittance (T) by "Lambert's Law" $-a\lambda L = \ln T_\lambda$

where the λ subscript refers to a specific wavelength.

A more useful term than absorption coefficient is the "characteristic absorption length" ($\pounds_a$). This is the length over which the transmittance drops to 1/eth (36.79%) of its original. Thus $T_a = \exp(-a\ \pounds_a)$

$\therefore\ \pounds_a = 1/a$ = characteristic absorption length.

As water is a selective absorber, with each wavelength of light having a characteristic absorption length it means that some wavelenghts are lost quicker than others thus clear ocean water soon loses the red part of the spectrum and transmits blue best.

There is no significant difference between the attenuation of pure water and sea water in the visible spectrum, but sea salts absorb weakly in the ultra violet region and absorption increases with the shorter wavelength.

In coastal and fresh water there exists variable quantities of "yellow substance" which is usually humic acids resulting from decay of organic plant material. This produces additional absorption which is strongest in the u.v. end of the spectrum.

(2) Scattering

J. Williams (1970) states there are 3 theories of the mechanism of scattering -

1. scatterers act as a reflector and the energy is reflected from the surface of the individual particle;
2. articles act as a refractor, refracting energy passing through the particle and as a diffractor, diffracting light energy that passes near to the particle;
3. assumes that the particle absorbs all energy arriving at it and reradiating in many different directions without any change in wavelength.

The type of scattering depends upon the size of particles relative to the wavelength of light being scattered.

(a) small compared to the wavelength - Rayleigh scattering ($\frac{1}{\lambda^4}$)

(b) comparable with wavelength - Mie scattering theory

(c) large compared to wavelength.

In the case (c) where the particles are relatively large with respect to the wavelengths of light (380-620 nm) (particle radius $> 10\lambda$) either mechanism 1 or 2 may be applied to scattering. This situation is common in the atmosphere with raindrops but is less common in the sea with the exception of some plankton.

The more common case in the sea; especially in coastal waters with suspended material is the case where the particle radii is less than 10λ (a & b) where the third theory for the mechanism of scattering is most applicable. Mie scattering theory is that the effective scattering cross-sectional area to the actual cross-sectional area of the particles is plotted against a non-dimensional parameter.

$$\frac{2\pi r\,(m^2 - 1)}{\lambda(m^2 + 1)}$$

where m is the relative index of refraction of the scatterers with respect to the medium

r is particle radius; λ is wavelength of light; $m = \frac{\text{speed of light in medium}}{\text{speed of light in partic}}$

This shows that when particles are small compared to wavelength the amount of energy scattered is quite small, but rises to a maximum as particle size increases. Further increase of r causes K to decrease and then oscillate about a value of 2.0.

See fig.19

If these results are replotted so that for a given particle size the relative scattering is determined for different wavelengths. Here we find that for very small particles (i.e.clays and silts) there is greatest scattering in the shorter (blue) wavelength - this is Rayleigh scattering where scattering is inversely proportional to the 4th power of wavelength.

See fig. 20

Scattering may also be termed in a similar way to absorption.

Scatterance (B) - the ratio of radiant flux scattered from a beam to

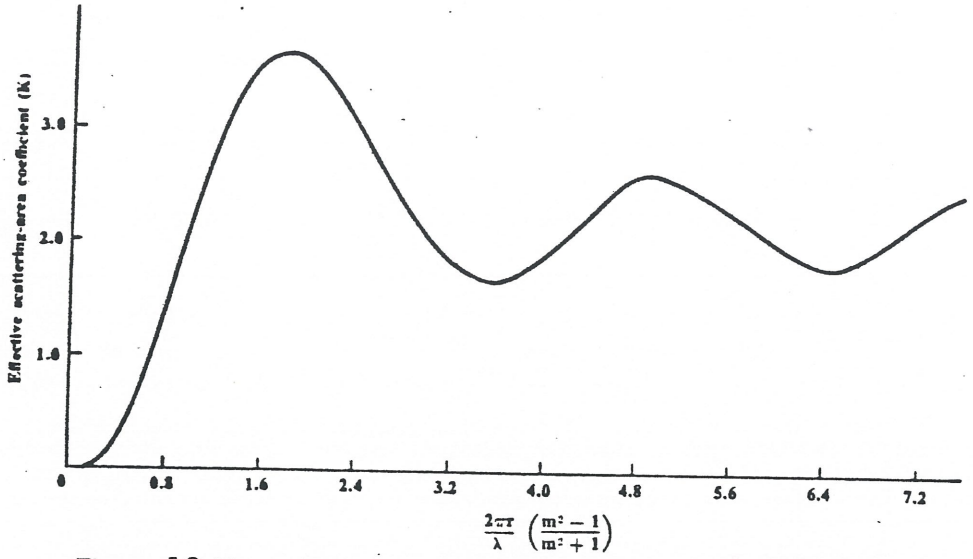


Figure 19 The variation of scattering with particle size and wavelength.
(After Williams, 1970)

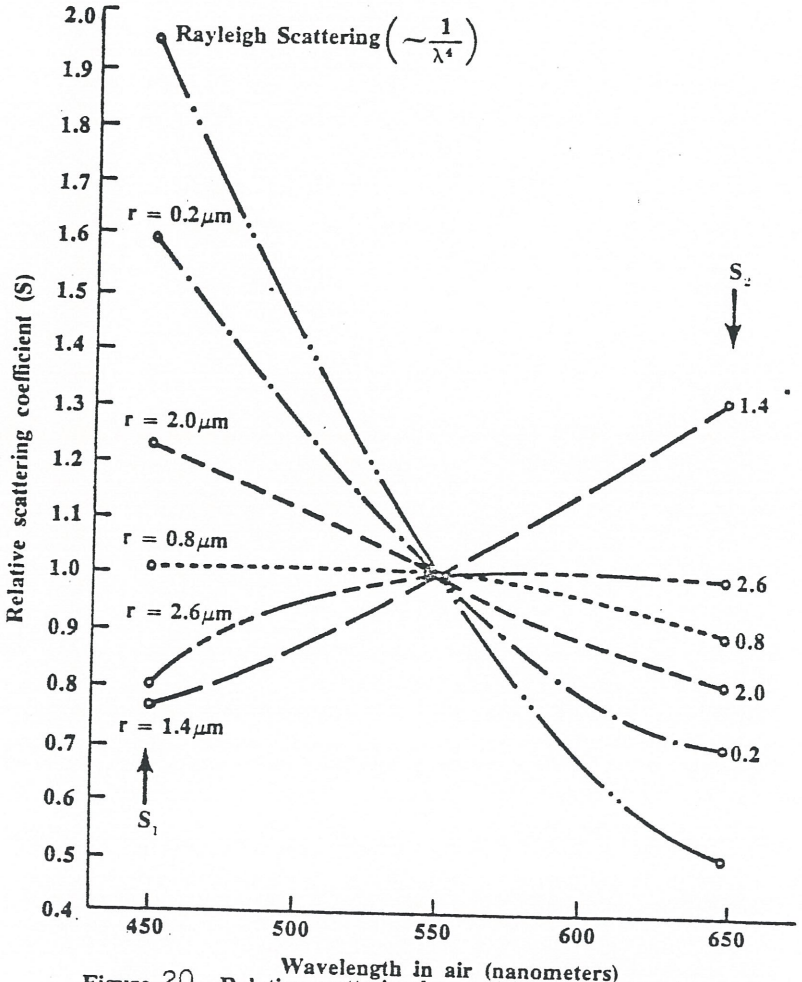


Figure 20 Relative scattering by particles of varying size.
(After Williams, 1970)

the incident flux where $B = \frac{F_B}{F_o} = \frac{F_o - F_{\Delta L}}{F_o}$ or

$$B = \frac{I_B}{I_o} = \frac{I_o - I_{\Delta L}}{I_o}$$

(Total) scattering coefficient (b) - internal scatterance from an infinitesimally thin layer of medium normal to the beam, divided by thickness (ΔL) of the layer (units of meter^{-1})

$$b = \frac{-\Delta B}{\Delta L} = \frac{-\Delta F_B}{F_o \Delta L}$$

assuming a homogeneous medium $bL = -\ln (I - B)$

and as for absorption $\frac{I_L}{I_o} = e^{-bl}$ $\quad I_L = I_o e^{-bl}$

$\pounds_b = 1/_b$ = characteristic scatter length

Together absorption and scattering give attenuation where:-

Attenuance (C)

$$C = A + B = I - T_{CL}$$

(Total) attenuance coefficient (c) - the internal attenuance of an infinitesimally thin layer of medium normal to the beam, divided by the thickness (ΔL) of the layer (units metre^{-1})

$$c = \frac{-\Delta C}{\Delta L} = \frac{-\Delta F_c}{F_o \Delta L}$$

$$c = a + b$$

and assuming a homogeneous medium: $cL = -\ln (I - C)$

$$l_L = l_o e^{-cL}$$

Characteristic attenuation length $\pounds_c = \frac{1}{c} = \frac{1}{a+b} = \frac{1}{\frac{1}{\pounds_a} + \frac{1}{\pounds_b}} = \frac{\pounds_a \pounds_b}{\pounds_a + \pounds_b}$

Most of the total attenuation is according to J. Williams (1973) due to absorption and this as stated before is wavelength dependent.

According to Duntley (1960) the beam (total) attenuation coefficient (c) can be estimated and similarly the characteristic attenuation length ($\mathfrak{L}_c$)

$$c = 4/d = \frac{1}{\mathfrak{L}_c}$$

$$\therefore \quad \mathfrak{L}_c = d/4$$

where d is the horizontal distance at which, in high light levels, a silhouetted object (black neoprene wet suit) can be sighted.

Note: If d is in feet ($c = ft^{-1}$), if d is in metres ($c = m^{-1}$)

(Irradiance) (E)

Irradiance (illumination) is defined as radiant flux incident upon an infinitesimal element of surface containing the point under consideration, divided by the area of that element.

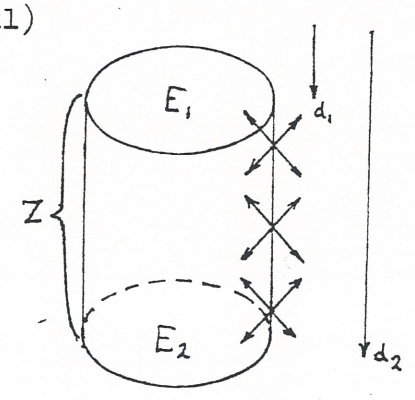
The illumination of an element of a surface will depend upon the angle of incidence of each ray. Those striking the surface normal to it will cause more illumination than a ray striking at an angle. The total illumination (irradiance) E :-

$$E = \frac{\Sigma F_i \ \text{Cos} \ \theta_i}{A}$$

where θ = angle of incidence to normal

Now considering the change of background illumination with depth. Light will get from one depth, d_1 to a deeper depth, d_2 by diffusion (scattering) in all directions so the light that gets to d_2 is that which has been scattered down from d_1. Due to scattering and having a larger path length than for beam transmittance a greater loss of intensity also occurs due to absorption (where absorption coefficient = a) (see Fig. 21)

in scatter to column = outscattering from column assuming scattering is a random process



$$E_2 = E_1 \ e^{-k \ Z}$$

$$I_2 = I_1 \ e^{-k \ Z}$$

Fig. 21 Irradiance

In the situation where light radiates from one single point source i.e. a torch, in all directions but none is reradiated back into the column from other sources, therefore the intensity is reduced by spherical spreading (inverse square law), so at distance r

$$I_r = I_o \exp(-kr)/r^2$$

In these cases k is the extinction coefficient (m^{-1})
and $1/k = \ell_k$ the characteristic extinction length (m)
$k < a$ and therefore $\ell_a > \ell_k$ as would be expected, since extinction is mainly a process of absorption which is intensified with the extended path lengths. The characteristic extinction length (ℓ_k) is much smaller than the characteristic absorption length (ℓ_c) because of the effects of scattering.

So where illumination is the main interest then the direction from which light arrives at the subject does not matter and the reduction of illumination with depth will depend upon the extinction coefficient (k). Seeing the illuminated object needs the light to travel directly from the target to the eye, then the ability to see it is dependent upon the total (beam) attenuance coefficient (c).

According to Duntley (1962) the extinction coefficient (k) can be estimated from the formulae:-

$$k = \frac{1.5}{d}$$

$$\text{and } \ell_k = \frac{d}{1.5}$$

where d is horizontal range at which a large dark object can be seen at high light levels

If d is in feet k is feet^{-1}, if d is in metres k is per metre. (C.C. Hemmings, 1965).

Other useful rules of thumb proposed by Duntley (1960) are

1. most objects can be sighted horizontally at a range of 4 to 5 times the distance

$= 1/\quad c - k \cos \theta$ where θ is the solar elevation

2. in natural waters provided $c = 4/d$ and $k = \frac{1.5}{d}$: $c = 2.7\,k$; then the downward sighting range of most objects = 7/8 the horizontal sighting range of large dark objects. (B.K. Gazey, 1970, gives the vertically downwards range as 3/4 the corresponding horizontal sighting range).

Contrast

Contrast is the difference between the radiance of object and background, divided by the background radiance.

$$C = \frac{L - L_b}{L_b}$$

If the value of C is + then the object is brighter than the background, if - then the background is brighter.

Inherent Contrast C_o

$$C_o = \frac{L_o - L_{bo}}{L_{bo}}$$

It is therefore the contrast between the radiances of the 2 objects (object L_o and background (L_{bo})at zero range from the object. The radiance of the object (L_b)depends upon its own reflective properties and the ambient light illuminating it, which depends upon its orientation. The radiance of the background (L_{bo})depends upon angle of sight and depth at which the object is situated.

Apparent Contrast C_r

$$C_r = \frac{L_r - L_{br}}{L_{br}}$$ at distance r from the object

and is dependent upon:-

1. attenuation (c) of the light from the object by absorption (a) and scattering (b).
2. the scattering of ambient light towards the observer through the entire length of the path of sight.

For an object to be seen the apparent contrast must not fall below the contrast threshold of the eye ($\sim$0.003 for man) otherwise only the background light will be seen (J. Williams, 1970). This is for an object of over 10 minutes of arc and a background illuminance of about 10 cd/m^2. The visual threshold apart from contrast also depends upon the ambient light level, the size of object itself and rate of flickering. Apparent contrast reduction by water follows the relationship

$$C_r = C_o \exp(-\{c + k \sin\theta\} r)$$

where c = total attenuation coefficient

k = extinction coefficient = $(a^2 - 2a L_b)^{\frac{1}{2}}$

B_b = back scatterance of light within a solid angle of 2π

r = distance from object

θ = angle of inclination of optical path to the horizontal.

In a horizontal optical path $\theta = 0^o$.

$$C_r = C_o \exp(-cr)$$

If the threshold contrast C_T is known then the visible range can be calculated

$$r = \frac{1}{c + k \sin\theta} \log_e C_o/C_T$$

In the horizontal case this simplifies to

$$r = \frac{1}{c} \log_e C_o/c_T$$

In the situation where a black body ($L_o = 0$) is silhouetted against background illumination, the inherent contrast (C_o) is -1 taking a value of $C_T = 0.02$. Then the "Duntley" approximation that the horizontal sighting range is roughly 4 times the attenuation length

$$\varepsilon_c = \frac{1}{c} \qquad \text{range} = 3.912/_c = 3.912\ \varepsilon_c \text{ where } 3.912 = \log_e \frac{C_o}{C_T}$$

In practice the range can vary from 2.5 up to 6.0 times ε_c and J. Williams (1970) suggests an average value of 3.5 as being appropriate. Typical values of c measured for light of 500 nm and their equivalent horizontal sighting ranges for a dark silhouetted object against natural backgrounds in normal daylight are given for various water masses by B.K. Gazey (1970) as follows:

Water mass	c (m^{-1})	$\varepsilon_c = \frac{1}{c}$ (m)	Sighting range (m) 4 ε_c
Clear oceanic	0.03	33.33	133.0
Normal oceanic	0.117	8.55	34.0
Turbid oceanic	0.174	5.75	23.0
Clear coastal	0.174	5.75	23.0
Normal coastal	0.342	2.92	11.7
Turbid coastal	0.755	1.32	5.3

In summary, J. Williams (1970) states that visual threshold is dependent upon 4 parameters:

1. the greater the contrast the easier an object can be seen;
2. up to a certain level, the greater the background luminance, the easier an object can be seen;
3. for any level of luminance small objects need more contrast to be seen;
4. a flashing light must be more intense than a steady one to be seen unless the flash duration is greater than about 0.5 seconds.

Until now we have considered an object to be invisible if the brightness contrast falls below the threshold contrast level, but

if the object is of a sufficiently different colour to the background then it will still remain visible (Hemmings & Lythgoe, 1965).

Colour Contrast

Coloured vision in man is due to the stimulation of three colour pigments in the eye. Any colour can thus be specified in terms of the tristimulus values, of the 3 pigments, red, green and blue. If the intensities of the 3 dominant component colours can be found for both the target and background then 3 distinct colour contrasts may be obtained in a similar way to the brightness contrast. Thus the actual chromatic contrast in terms of a particular colour would be more descriptive of the visual threshold than the apparent luminance contract which might be quite misleading (J. Williams, 1973).

A further factor is that in photopic vision in man (and in most fish) vision is coloured; with different sensitivities to different wavelengths so therefore threshold intensities for each colour will vary (being most sensitive to yellow-green light). At night when scotopic vision exists man's peak sensitivity shifts to blue green light (= 50 nm shorter wavelength) and contrast is due to relative brightness, as actual colour perception does not exist.

In fish due to different pigments the peak sensitivities are generally displaced from that in man. According to Lythgoe (1965) it is thought that scotopic colour vision might exist in some fish. If this is so then colour contrast would also be important at night though at greatly reduced brightnesses. According to Protasov (1970) more elasmobranchs, e.g. Raia clavata (thornback skate) have only rod (non-colour) dark adapted vision and only apparent contrast is relevant in their vision over the range of wavelengths that they can perceive. (See fig. 16)

Results

Plymouth Sound and surrounding waters at depth of approximately 14m.

1. Low visibility water (Secchi disc depths <3.5m)

- Diver observation (Duke Rock:- $\mathfrak{L}_C$ = 0.88m $\mathfrak{L}_K$ = 2.36m)

  Table of results (see Table 3) and graphical plot (see Fig. 22)

- Fishing results

  Tables of results (2) (see Tables 4 and 5)

  Calculations of proportion of total fish in each net (see Table 6)

  Plot of 1 - relative proportion of catch, and diver observed ranges against colours of nets; in order of brightness (see Fig. 23)

- Analysis

  Scatter diagram of mean diver observed ranges against proportion of catch, for each net colour (see Fig. 24)

  Calculation of correlation coefficient for above plot (see Correlation Coefficient in Appendix).

DATE 7/4/81 SITE Duke Rock DEPTH 15m

TIME SET 10-30 TIME HAULED 11-10 TIME FISHED 40 min.

SECCHI DISC DEPTH 1) _____ 2) _____ AV. _____

HORIZONTAL BLACK BODY DISTANCE; AT NET DEPTH 1) 3.0 m 2) 4.1 m AV. 3.55 m.

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
BALLAN WRASSE	2						1		3
HORIZONTAL RANGE (m)									OBSERVER'S NAME
	1·5	2·3	2·1	1·1	1·9	2·4	1·4	1·1	S.M.
	2·1	2·5	2·0	1·0	1·7	2·3	1·5	1·5	M.B.
MEAN RANGE (m)	1·8	2·4	2·05	1·05	1·8	2·35	1·45	1·3	
ORDER OF INCREASING VISUAL RANGE ≡ INCREASING CONTRAST	=4	8	6	1	=4	7	3	2	
Total in each net	2						1		Total Catch = 3 fish

Sea State:- Calm/~~Rough~~ Average Surface Irradiance/hour fished ___ mW

Wind: NE 2-3 Sky:- Overcast/~~Cloudy/Clear~~

Comments: STRONG EBB TIDE. FISH CATCHES APPARENTLY NOT CONNECTED TO VISUAL CONTRAST AS SEEN BY DIVERS. BOTTOM is Broken shell, mud & single

MAXIMUM HORIZONTAL SIGHTING RANGES (METRE)

MAXIMUM HORIZONTAL DISTANCE AT WHICH EACH COLOUR NETTING AND BLACK BODY (DIVER) COULD BE SEEN BY EACH DIVER (INDICATED BY INITIALS) AT DEPTH OF 15m NEAR DUKE ROCK, PLYMOUTH SOUND. ($c = 1.125\ m^{-1}$, $\ell_c = 0.88\ m$; $k = 0.42\ m^{-1}$; $\ell_K = 2.36\ m$.)

(DATE: 7/4/81)

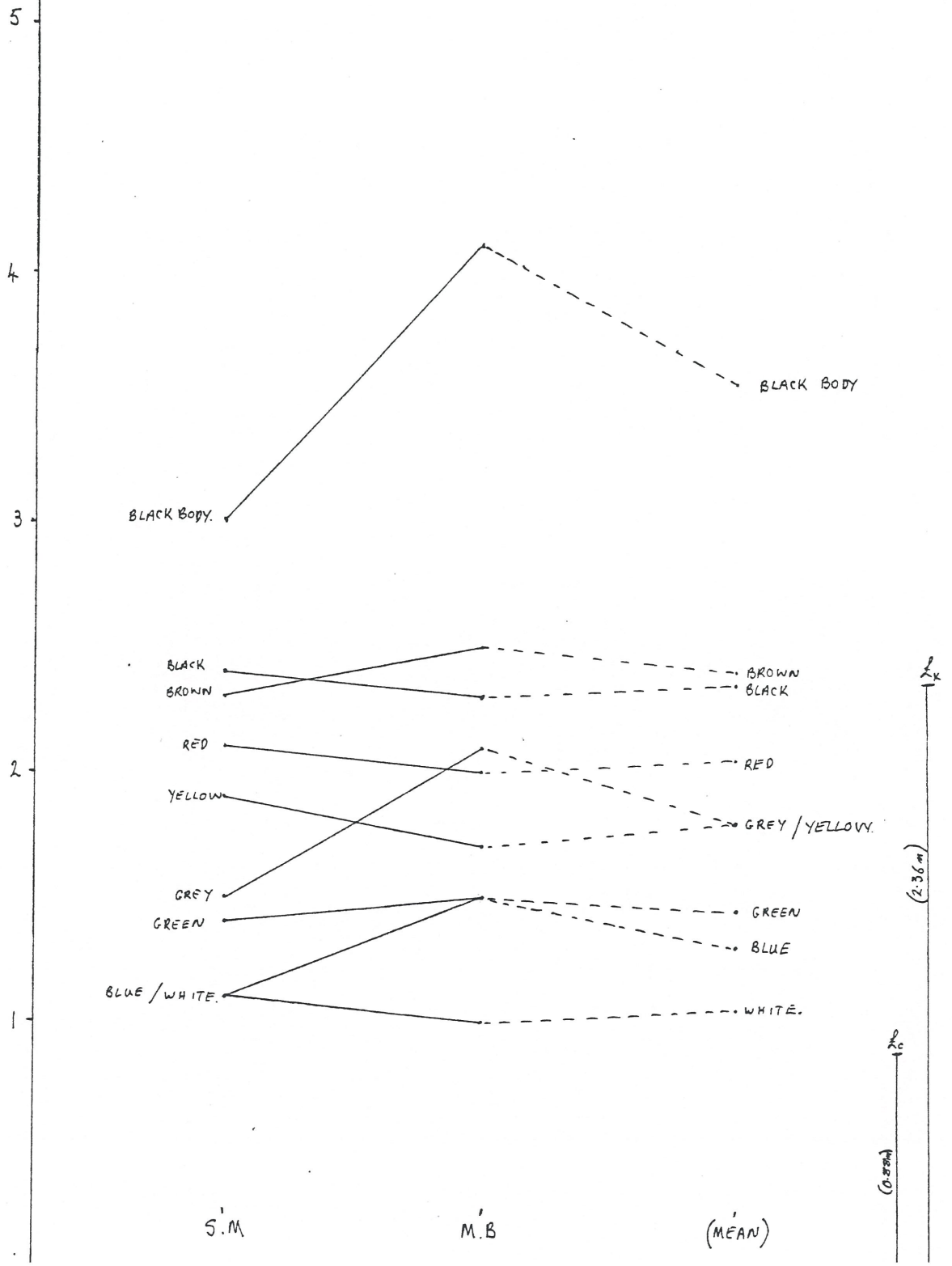


Table 4

DATE 17th/1/81 SITE INSIDE WEST END OF BREAKWATER, PLYMOUTH SOUND DEPTH 14 m.

TIME SET 0820 TIME HAULED 1530 TIME FISHED 7 hr 10 min

SECCHI DISC DEPTH 1) 2·4 m 2) 2·4 m. AV. 2·4 m.

% TRANSMITANCE AT NET DEPTH 1) NOT AVAILABLE 2) ____ AV. ____

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
BASS					1				1
Total in each net	0	0	0	0	1	0	0	0	Total Catch = 1 fish

Sea State:- ~~Calm~~/Rough

Average Surface Irradiance/hour fished ___ mW

Wind: W-NW 8-9 GUSTING 10 Sky:- ~~Overcast~~/Cloudy/~~Clear~~

Comments: BOTTOM SAND AND SHELL. A LOT OF STARFISH ALONG FOOT ROPE, SOME CAUSING A SLIGHT ROLL. NO SEAWEED.

NOTE: FISHED DURING DAY LIGHT.

BLACK BODY DISTANCE BETWEEN 2 DIVERS WAS APPROXIMATELY 2 m. ACCORDING TO DUNTLEY (1960)

TOTAL ATTENUATION COEFFICIENT (c) = $\frac{4}{d}$ m^{-1} $\therefore$ $c = \frac{4}{2} = 2\,m^{-1}$; $\ell_c = \frac{2}{4} = 0.5\,m.$

EXTINCTION COEFFICIENT (k) = $\frac{1.5}{d}$ m^{-1} $\therefore$ $k = \frac{1.5}{2} = 0.75\,m^{-1}$; $\ell_k = \frac{2}{1.5} = 1.33\,m.$

Table 5

DATE 3-4/3/81 SITE OUTSIDE EAST END OF BREAKWATER DEPTH 14m

TIME SET 1100 TIME HAULED 1400 TIME FISHED 27 hour.

SECCHI DISC DEPTH 1) 1·5m 2) 5·2m AV. 3·4 m.

% TRANSMITANCE AT NET DEPTH 1) NOT AVAILABLE 2) ——— AV. ———

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
POLLACK	1	2	3		1		1	3	11
COALFISH						1			1
Total in each net	1	2	3	0	1	1	1	3	Total Catch = 12 fish

Sea State:- Calm/~~Rough~~ Average Surface Irradiance/hour fished ___ mW

Wind: S 1-2 Sky:- Overcast/~~Cloudy/Clear~~

Comments:

BOTTOM ROCK AND KELP, HAD TO DIVE TO CLEAR GREEN NET OFF BOILER. SPRING TIDE; NO MOON.

Table 6

Depth: Shallow (14m, 14m)

Water: Turbid (Secchi disc depth 2.4 and 3.4m)

	Brown	Black	Grey	Red	Green	Yellow	Blue	White	Total
	0	0	0	0	0	1	0	0	1
	2	1	1	3	1	1	3	0	12
Total catch	2	1	1	3	1	2	3	0	13
Proportion of catch	0.154	0.077	0.077	0.231	0.077	0.154	0.231	0.00	
1- prop. of catch	0.846	0.923	0.923	0.769	0.923	0.846	0.769	1.00	

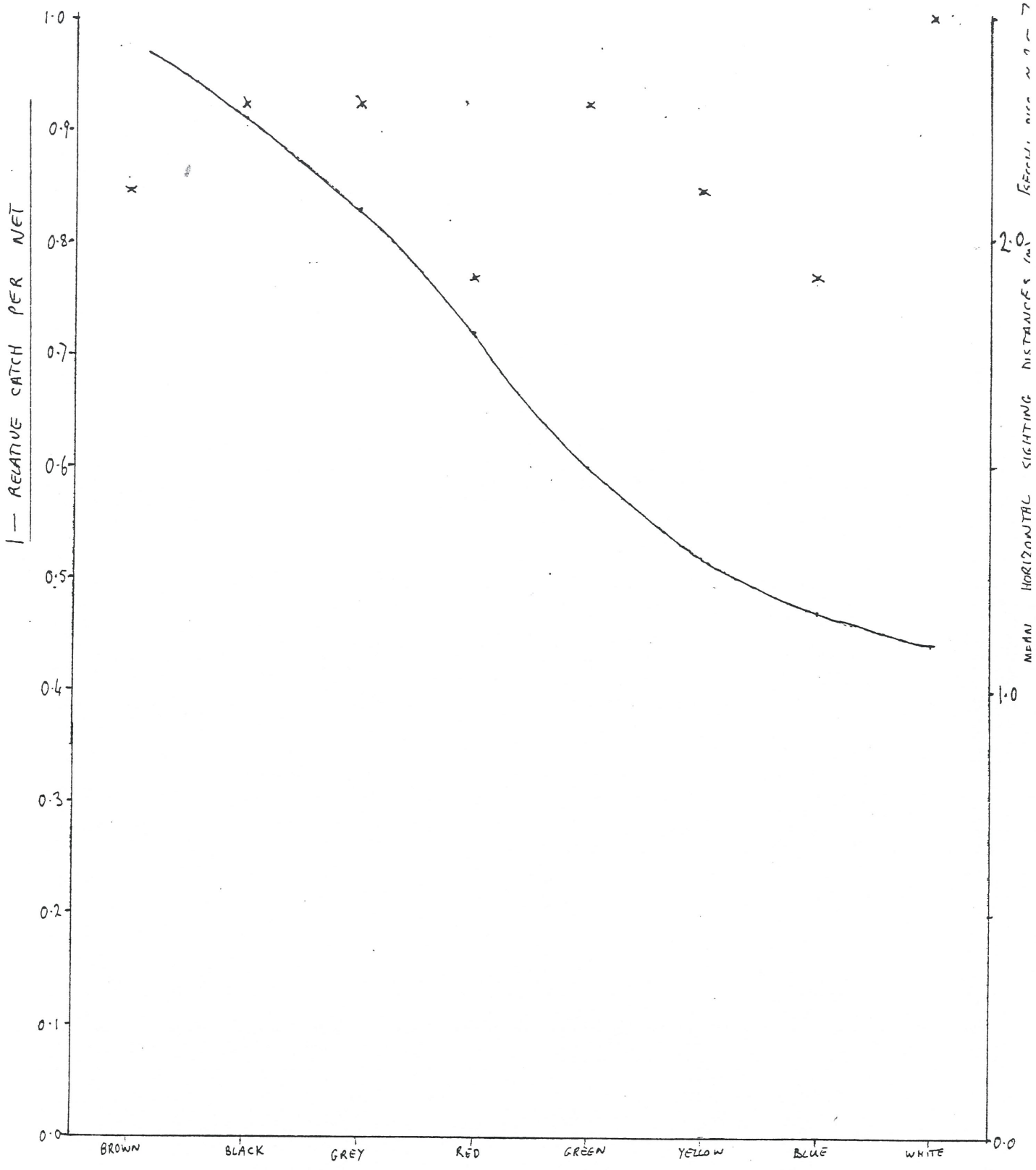
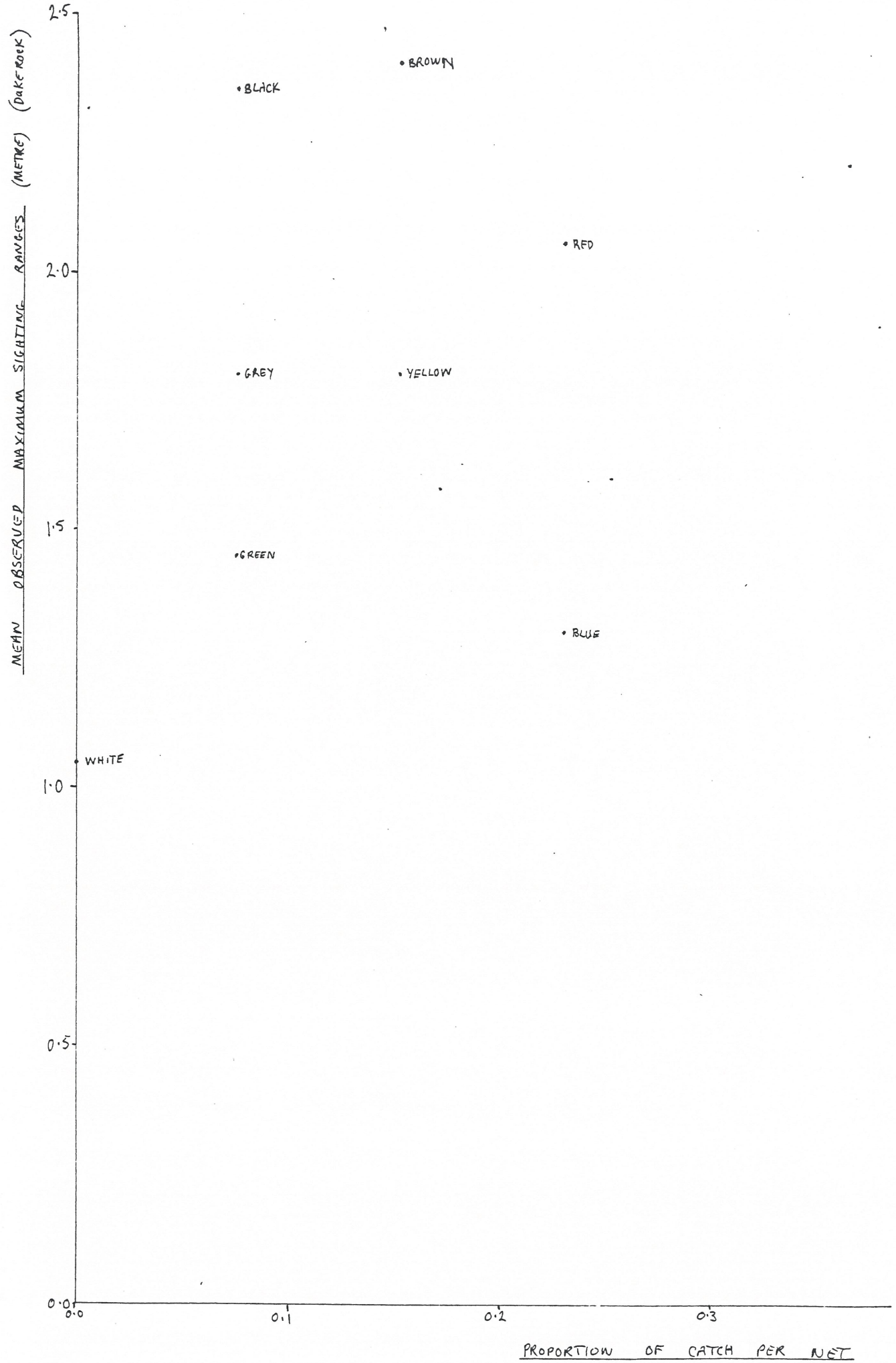


fig 23 : RESULTS FROM FISHING AT 14m IN DIRTY WATER (SECCHI DISC DEPTH = 2·4 AND 3·4m) IN PLYMOUTH AREA ON 17/1 AND 3-4/3

Nº OF TIMES FISHED = 2 ; TOTAL Nº OF FISH CAUGHT = 13

A · Scatter Diagram of Diver . Observed Visual Ranges Against Proportions Of The Total Fish Catches In Each Net ; For Similar Water Conditions



Calculation of Correlation Coefficient (r) for catches (X) to observed visual ranges (Y); in turbid water, Plymouth

	Brown	Black	Grey	Red	Green	Yellow	Blue	White	
Proportion of catches (X)	0.154	0.077	0.077	0.231	0.077	0.154	0.231	0.00	=
	Total 1.00 = ΣX								
Visual ranges (Y)	2.4	2.35	1.8	2.05	1.45	1.8	1.3	1.05	=
	Total 14.2 = ΣY								
X^2	0.024	0.006	0.006	0.053	0.006	0.024	0.053	0.00	=
	Total 0.1719 = ΣX^2								
Y^2	5.76	5.52	3.24	4.20	2.10	3.24	1.69	1.10	=
	Total 26.86 = ΣY^2								
X Y	0.369	0.181	0.1386	0.474	0.112	0.277	0.300	0.00	=
	Total 1.852 = ΣXY								

$$r = \frac{\Sigma XY - (\Sigma X \Sigma Y)/n}{\sqrt{[\Sigma X^2 - (\Sigma X)^2/n][\Sigma Y^2 - (\Sigma Y)^2/n]}}$$

$$= \frac{1.852 - (1.00\ 14.2)/8}{\sqrt{[\ 0.1719 - (1.00)^2/8][\ 26.86 - (14.2)^2/8\ ]}}$$

$$\frac{0.077}{\sqrt{[0.0469\ ][1.655\ ]}} = \frac{0.077}{0.2786} = \underline{0.276}$$

This value suggests a slight positive relationship, i.e. catches are proportional to visibility; the more visible nets would catch most.

This apparent outcome seems unlikely and is almost certainly due to white net having low visibility and not catching. If the white result is excluded then the correlation coefficient becomes -0.1577; this is still insignificant though its sign does suggest the expected correlation between lower visibility and better catches.

As this result is based upon only two periods fishing with low catch rates then any results will be heavily influenced by random factors.

With much more data these would tend to be smoothed out, to reveal any correlations between diver observed visibility and fish catches in these water conditions and depth; if in fact one exists.

2. Intermediate clarity of water (Secchi disc depths 3.5-5.5m)

- Diver observation (Cawsand Bay:- ε_c = 1.49m ε_K = 3.97m)

  Table of results (see Table 7) and graphical plot (see Fig. 25)

- Fishing results

  Tables of results (3) (see Tables 8-10)

  Calculation of proportion of total fish in each net (see Table 11)

  Plot of 1- relative proportions of total catch and diver observed ranges against colours of nets; in order of brightness (see Fig. 26)

- Analysis

  Scatter diagram of mean diver observed ranges against proportion of catch, for each net colour (see Fig. 27)

  Calculation of correlation coefficient for above plot

DATE 7/2/81 SITE CAWSAND BAY. DEPTH 14 m.

TIME SET 10-15 TIME HAULED 1130 TIME "FISHED" 1 hr 15 min.

SECCHI DISC DEPTH 1) 3·70 m 2) ____ AV. 3·70 m

HORIZONTAL BLACK BODY DISTANCE; AT NET DEPTH 1) 5·4 m [M.B.] 2) 6·5 m [S.M.] AV. 5·95 m.

Net Colour / HORIZONTAL RANGE (m)	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Grey Mono	OBSERVER'S INITIALS
	4·0	4·2	3·8	3·0	2·8				1·7	K. B.
	4·1	4·4	4·2	3·2	2·1	3·2	2·5	2·4	2·0	S. M.
	4·1	4·0	3·8	2·8	2·0				2·1	P. H.
MEAN RANGE (m)	4·07	4·20	3·93	3·00	2·30				1·93	
(S.M. ~ MEAN)	0·03	0·20	0·13	0·20	-0·30				0·17	MEAN CORRECTION = 0·07
CORRECTED MEANS (S.M − 0·07)						3·13	2·43	2·33		
MEAN RANGES (m)	4·07	4·20	3·93	3·00	2·30	3·13	2·43	2·33	1·93	
ORDER OF INCREASING VISUAL RANGE ≡ INCREASING ± CONTRAST	8	9	7	5	2	6	4	3	1	

Sea State:- ~~Calm~~/Rough Average Surface Irradiance/hour fished ___mW

Wind: SW 4-5 Sky:- Overcast/~~Cloudy/Clear~~

Comments: THE FLEET OF NETS WERE SET ONLY DURING DIVING OPERATION. THEY WERE LAYED ACROSS TIDE ON SAND RIDGES, AND SHOWED ONLY SLIGHT LAYING DOWN (<10%). FOR SAFETY THE DIVERS OPPERATED ON THE DOWN TIDE SIDE OF THE NETS. AT VERY CLOSE RANGE THE YELLOW NET APPEARED BRIGHT AND HIGHLY VISIBLE, BUT CONTRAST WAS RAPIDLY LOST WITH INCREASING RAINGE. IN THE NET WHEN HAULED WERE NUMEROUS STARFISH DISTRIBUTED THROUGHOUT AND AN EDIBLE CRAB ENTANGLED IN THE BLUE NET. PHOTOGRAPHIC OBSERVATIONS WERE ALSO MADE USING ASA 400 FILM, 1/60th SHUTTER SPEED AND A CAMERA SETTING OF f/2·5 (SHOULD HAVE BEEN f/2, AS LIGHT METER READING OFF BLACK GLOVE WAS f/1; BUT f/2·5 WAS LOWEST CAMERA SETTING THEREFORE ALL PHOTOGRAPHS WERE UNDER EXPOSED.)

MAXIMUM HORIZONTAL DISTANCES AT WHICH, EACH COLOUR NETTING AND BLACK BODY (DIVER), COULD BE SEEN BY EACH DIVER (INDICATED BY INITIALS), AT 14M DEPTH IN CAWSANDS BAY, PLYMOUTH SOUND. ($c = 0.67\ m^{-1}$, $\ell_c = 1.49\ m$; $k = 0.25\ m^{-1}$, $\ell_k = 3.97\ m$).

(DATE : 7/2/81)

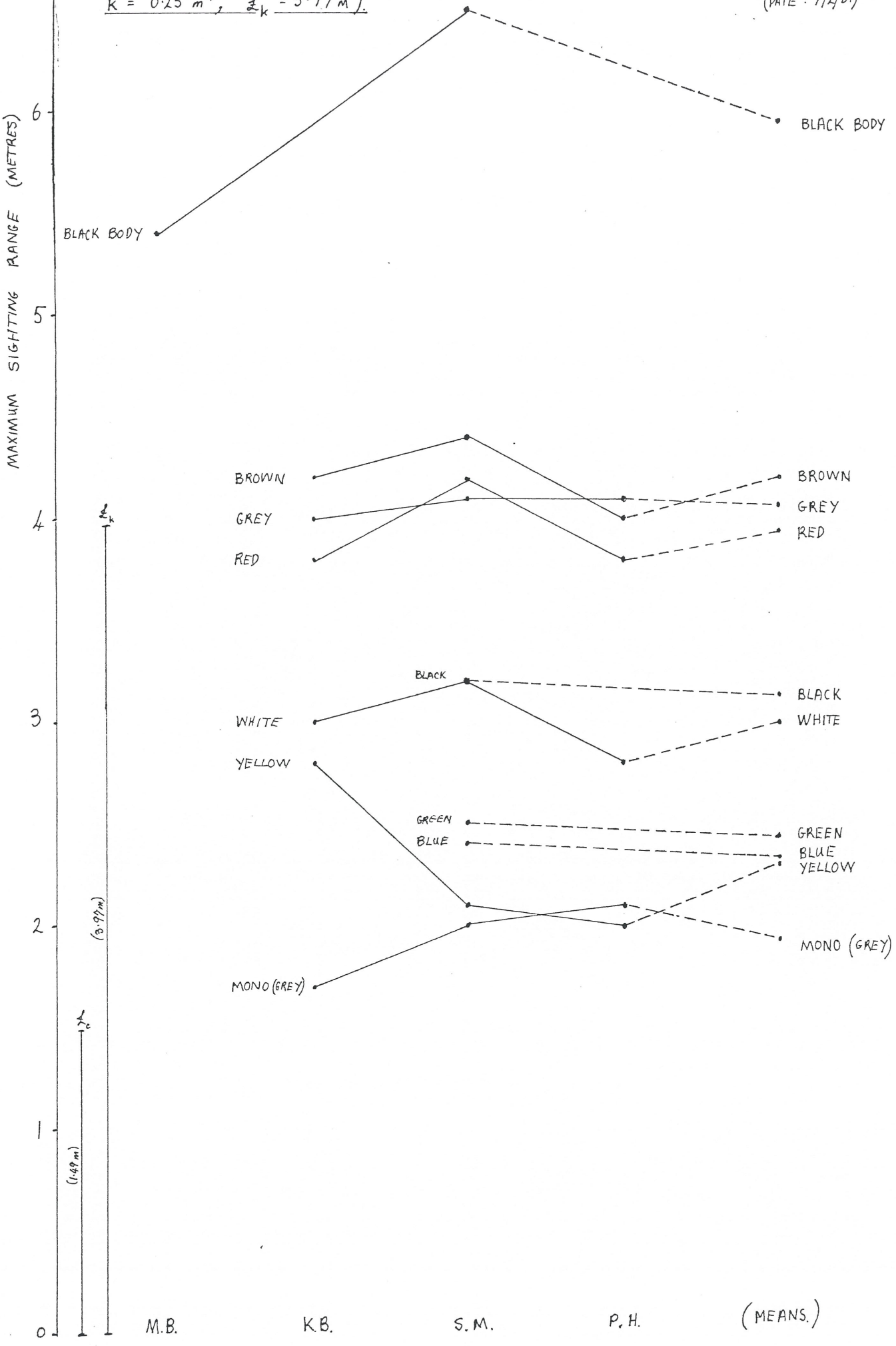


Table 8

DATE 3/12/80 SITE BELOW STANDON HEIGHT, PLYMOUTH SOUND, DEVON. DEPTH 12 m.

TIME SET 0900 TIME HAULED 1500 TIME FISHED 6 hr.

SECCHI DISC DEPTH 1) 4·65 m 2) 4·55 m AV. 4·6 m

% TRANSMITANCE AT NET DEPTH 1) 93% 2) 93% AV. 93%

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
Total in each net	0	0	0	0	0	0	0	0	Total Catch = 0 fish

Sea State:- Calm/~~Rough~~ Average Surface Irradiance/hour fished ___ mW

Wind: N 1-2 Sky:- ~~Overcast/Cloudy/~~Clear

Comments: NETS BOTTOM SET OVER ROCK GULLIES. THE RED NET WAS FOULED BY A RUSTY LOBSTER POT FRAME. NO WEED.

NOTE: FISHED DURING DAY. BRIGHT SUNSHINE.

Table 4

DATE 3rd-4th/12/80 SITE BELOW MOUNT EDGECOMBE PLYMOUTH SOUND DEPTH 7m.

TIME SET 1615 TIME HAULED 0830 TIME FISHED 16 hr 15 min

SECCHI DISC DEPTH 1) 4.55m. 2) —— AV. 4.55m.

% TRANSMITANCE AT NET DEPTH 1) 93% 2) —— AV. 93%

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
POLLOCK	1		1				2		4
BALLAN WRASSE								2	2
(CORMORANT)							(1)		(1)
Total in each net FISH (BIRDS)	1	0	1	0	0	0	2 (1)	2	Total Catch = 6 fish

Sea State:- Calm/~~Rough~~ Average Surface Irradiance/hour fished ——mW

Wind: N 1-2 → NW 3-4 Sky:- ~~Overcast~~/Cloudy/~~Clear~~

Comments: NETS BOTTOM SET OVER ROCK AND SHINGLE PATCHES, VERY LITTLE WEEDIN NET. CORMORANT WAS CAUGHT APPROXIMATELY 0·3 m ABOVE A POLLOCK IN THE GREEN NET.

NOTE: FISHED OVER NIGHT.

~~Table 10~~

DATE 4-5/3/81 SITE 4 CABLE SOUTH OF THE BREAKWATER DEPTH 15m.

TIME SET 1400 TIME HAULED 1400 TIME FISHED 24

SECCHI DISC DEPTH 1) 5·2m 2) ____ AV. 5·2m

% TRANSMITANCE AT NET DEPTH 1) NOT AVAILABLE 2) ____ AV. ____

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
POLLACK		1					2		3
BASS	1								1
BALLAN WRASSE								1	1
Total in each net	1	1	0	0	0	0	2	1	Total Catch = 5 fish

Sea State:- ~~Calm~~/Rough Average Surface Irradiance/hour fished ___ mW

Wind: S-SW 4-5 Sky:- Overcast/~~Cloudy/Clear~~

Comments:

Table 11

Depth: Shallow (7, 12, 15m)

Water: Less turbid (Secchi disc depths 4.6m, 4.55m and 5.2m)

	Brown	Black	Grey	Red	Green	Yellow	Blue	White	Total
	0	0	0	0	0	0	0	0	0
	0	0	1	1	2	0	2	0	6
	1	0	1	0	2	0	1	0	5
Total catch	1	0	2	1	4	0	3	0	11
Proportion of catch	0.091	0.0	0.182	0.091	0.364	0.0	0.273	0.0	
1- prop. of catch	0.909	1.0	0.818	0.909	0.636	1.0	0.727	1.0	

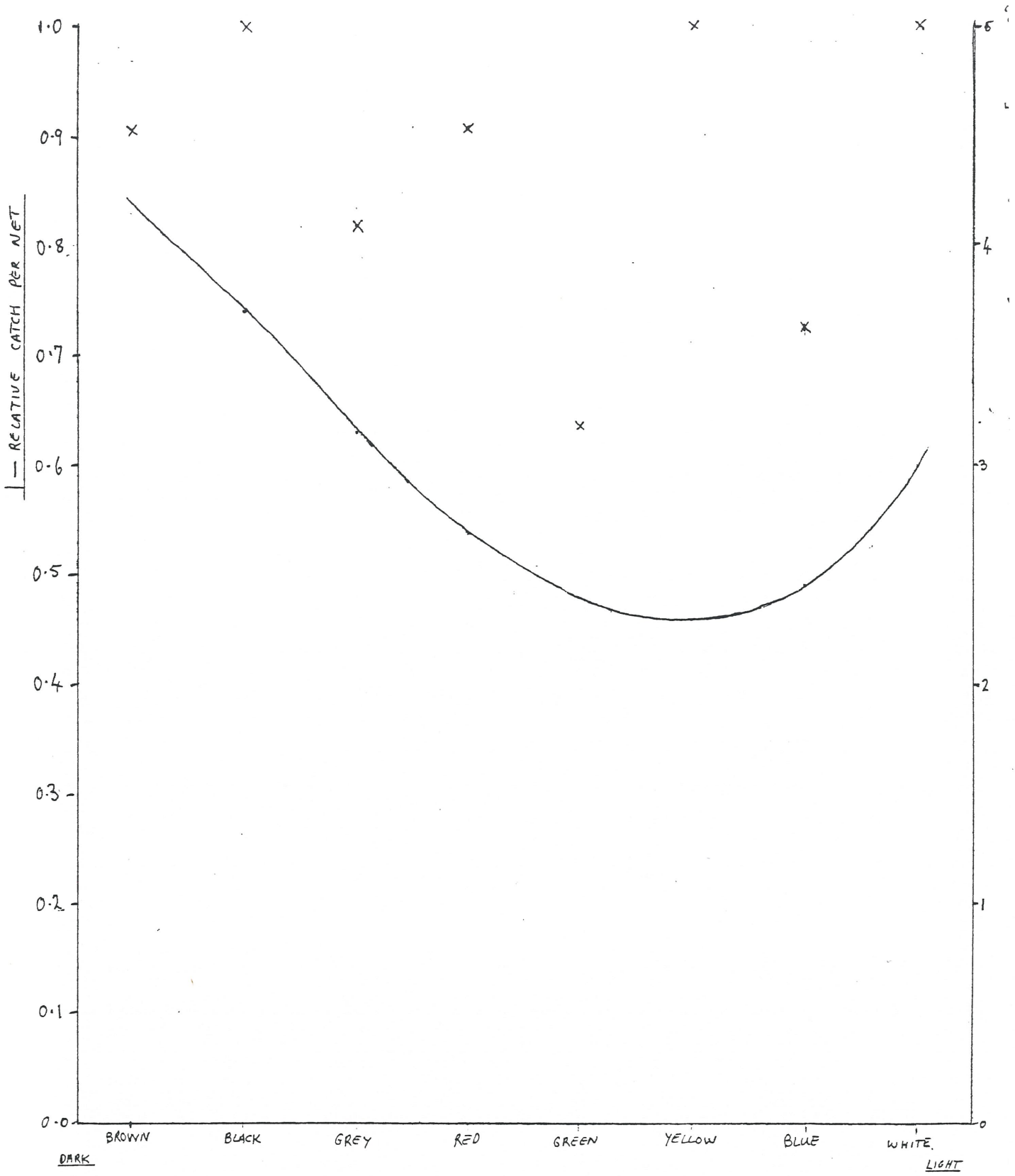
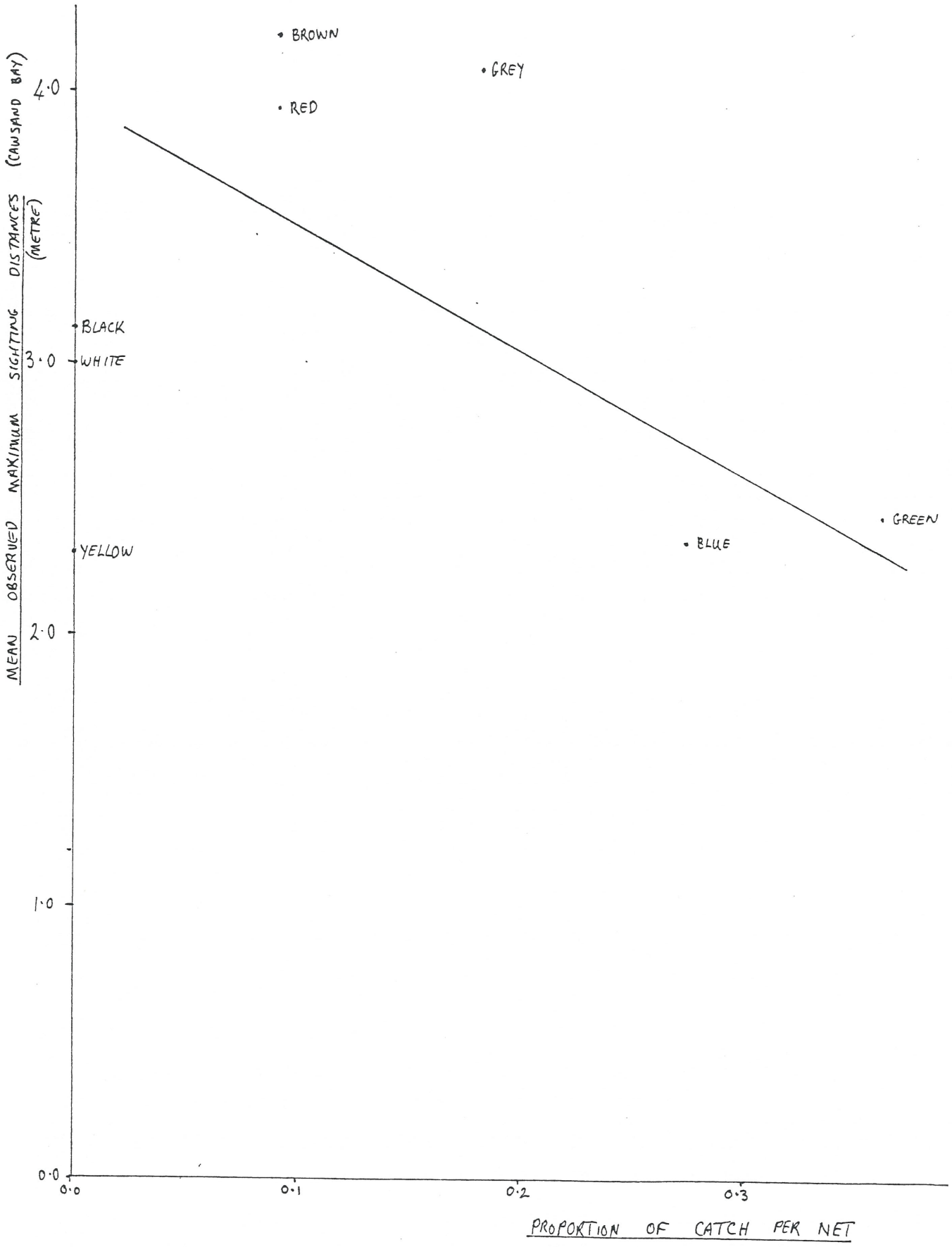


fig 26 : RESULTS FROM FISHING AT DEPTHS FROM 7 – 15 m IN PLYMOUTH AREA (SECCHI DISC DEPTHS = 4·6, 4·55 AND 5·2 m) ON 3/12, 3-4/12 AND 4-5/3/81

Nº OF TIMES FISHED = 3 (BLANK ON 3/12/80) ; TOTAL Nº OF FISH CAUGHT = 11

Fig 2.1 :

A SCATTER DIAGRAM OF DIVER OBSERVED VISUAL RANGES AGAINST PROPORTION OF THE TOTAL FISH CATCHES IN EACH NET ; FOR SIMULAR WATER CONDITIONS



Calculation of Correlation Coefficient (r) for catches (X) to observed visual ranges (Y); in less turbid water

	Brown	Black	Grey	Red	Green	Yellow	Blue	White	
Proportion of catches (X)	0.091	0.0	0.182	0.091	0.364	0.0	0.273	0.0	=
	Total 1.00 = ΣX								
Visual ranges (Y)	4.20	3.13	4.07	3.93	2.43	2.30	2.33	3.00	=
	Total 25.39 = ΣY								
X^2	0.0083	0.0	0.033	0.0083	0.133	0.0	0.0745	0.0	=
	Total 0.2567 = ΣX^2								
Y^2	17.64	9.797	16.56	15.44	5.905	5.29	5.43	9.00	=
	Total 85.07 = ΣY^2								
X Y	0.38	0.0	0.741	0.36	0.88	0.0	0.636	0.0	=
	Total 3.00 = XY								

$$r = \frac{3.00 - (1.00 \cdot 25.39)/8}{\sqrt{[0.2567 - (1)^2/8][85.07 - (25.39)^2/8]}}$$

$$= \frac{-0.17375}{\sqrt{(0.1317)(4.4885)}} = \frac{-0.1737}{0.7688} = \underline{-0.226}$$

This suggests a slight negative correlation, i.e. the higher the observed net visibility the less it catches.

3. Clear water (Secchi disc depths > 5.5m)

- Diver observation (Peader Rock, Whitesand Bay:- $\mathcal{E}_c$ = 1.87m

  $\mathcal{E}_K$ = 5.00m)

  Table of results (see Table 12) and graphical plot (see Fig. 28)

  Photographs of nets (see Plates 3-11)

- Fishing results

  Tables of results (5) (see Tables 13-17)

  Calculation of proportion of total catch in each net (see Table 18)

  Plot of 1- relative proportion of total catch and diver observed ranges against colours of nets; in order of brightness as determined by photographs (see Fig. 29)

- Analysis

  Scatter diagram of mean diver observed ranges against proportion of catch for each net colour.

  Calculation of correlation coefficient for above plot (see Fig. 30)

Table 12

DATE 21/2/81 SITE NEAR PEADER ROCK; WESTERN GEARS, WHITSANDS BAY. DEPTH 14 m.

TIME SET 0900 TIME HAULED 11 15 TIME FISHED 2hr 15 min

SECCHI DISC DEPTH 1) 9.5 m 2) — AV. 9.5 m

HORIZONTAL BLACK BODY DISTANCE ; AT NET DEPTH 1) 7.5 m [S.M] 2) — AV. 7.5 m

Net Colour / HORIZONTAL RANGE (m)	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Grey MONO	OBSERVER'S INITIALS
	3·5	5·1	5·3	4·5	3·2	5·3	3·0	3·7	2·6	S. M.
	3·4	4·9	4·8	4·3	3·8	3·8	3·2	3·7	2·8	P. H.
MEAN RANGES (m)	3·45	5·00	5·05	4·40	3·50	4·55	3·10	3·70	2·70	
ORDER OF INCREASING VISUAL RANGE = INCREASING ± CONTRAST	3	8	9	6	4	7	2	5	1	

Sea State:- ~~Calm~~/Rough

Average Surface Irradiance/hour fished — mW

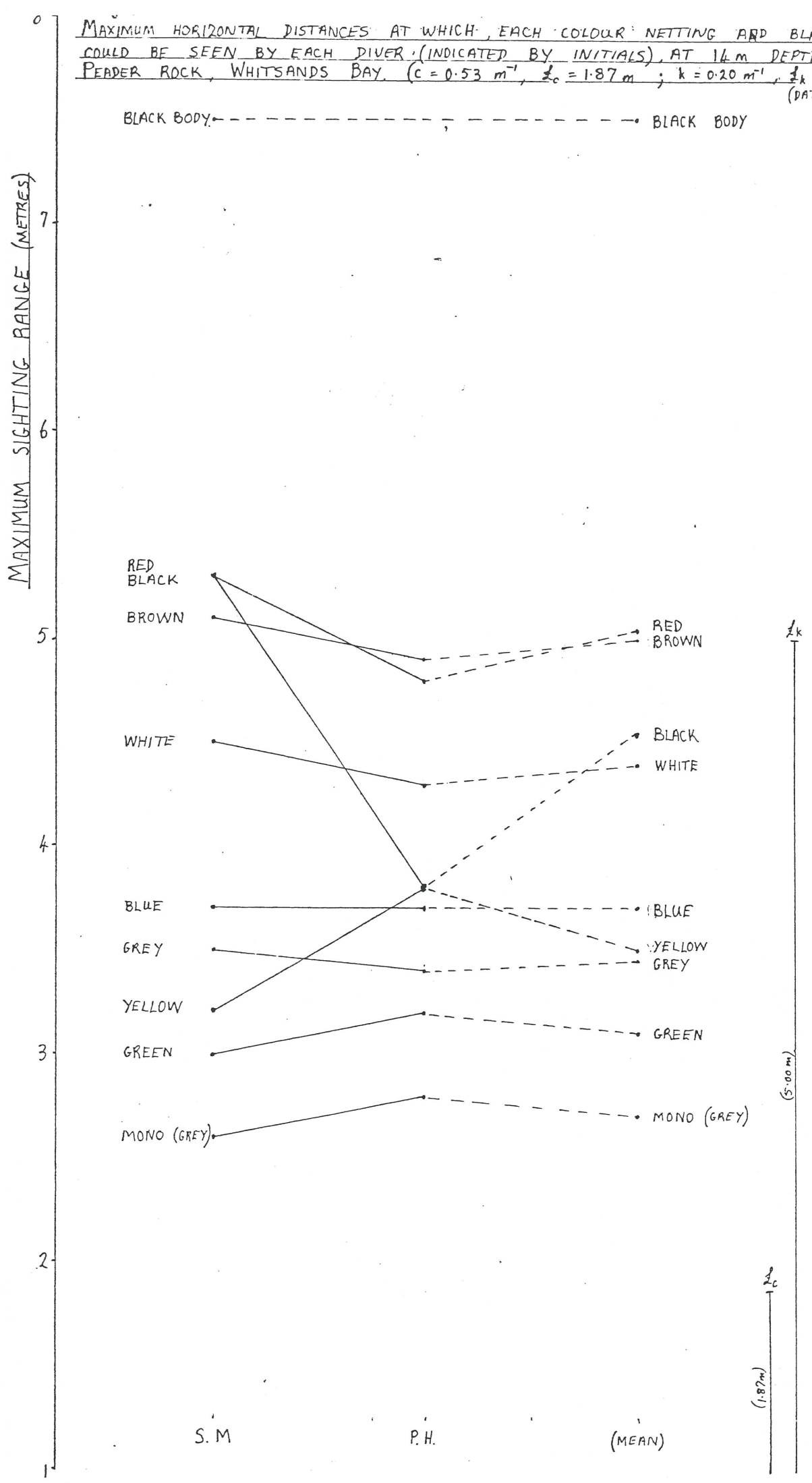
Wind: SE 3 - 5

Sky:- Overcast/~~Cloudy/Clear~~

Comments: THE NETS WERE SET ACROSS TIDE FOR THE PURPOSE OF DIVING. THE BOTTOM WAS MAINLY SAND WITH THE OCCASIONAL ROCK OUTCROP. 1 WRASSE WAS SEEN RESTING IN THE AREA OF THE NETS, BY DIVERS.

PHOTOGRAPHIC OBSERVATIONS WERE ALSO MADE USING ASA 400 FILM, $\frac{1}{30}$ SHUTTER SPEED AND AN APERTURE OF f/4 (CORRECTED FROM A LIGHT METER READING OF f/2 OFF A BLACK GLOVE)

MAXIMUM HORIZONTAL DISTANCES AT WHICH, EACH COLOUR NETTING AND BLACK BODY (DIVER) COULD BE SEEN BY EACH DIVER (INDICATED BY INITIALS), AT 14 m DEPTH NEAR PEADER ROCK, WHITSANDS BAY. ($c = 0.53\ m^{-1}$, $l_c = 1.87\ m$; $k = 0.20\ m^{-1}$, $l_k = 5.00\ m$.)
(DATE: 21/2/81)



Photograph of the nets at a depth of 14m. in Whitsand Bay on 21.2.81. Using Kodak Ektachrome film, ASA 400, at 1/30th and f4 with an actual range of 1.5m horizontally using natural light. (Also given are the mean diver assessments of the visual ranges on the same occasion). Secchi disc depth = 9.5m; and $£_c$ = 1.87m and $£_k$ = 5.0m. as derived from a "Black body" distance of 7.5m.

No photograph available

Plate 3 Blue net:- (mean diver visual range = 3.7m)

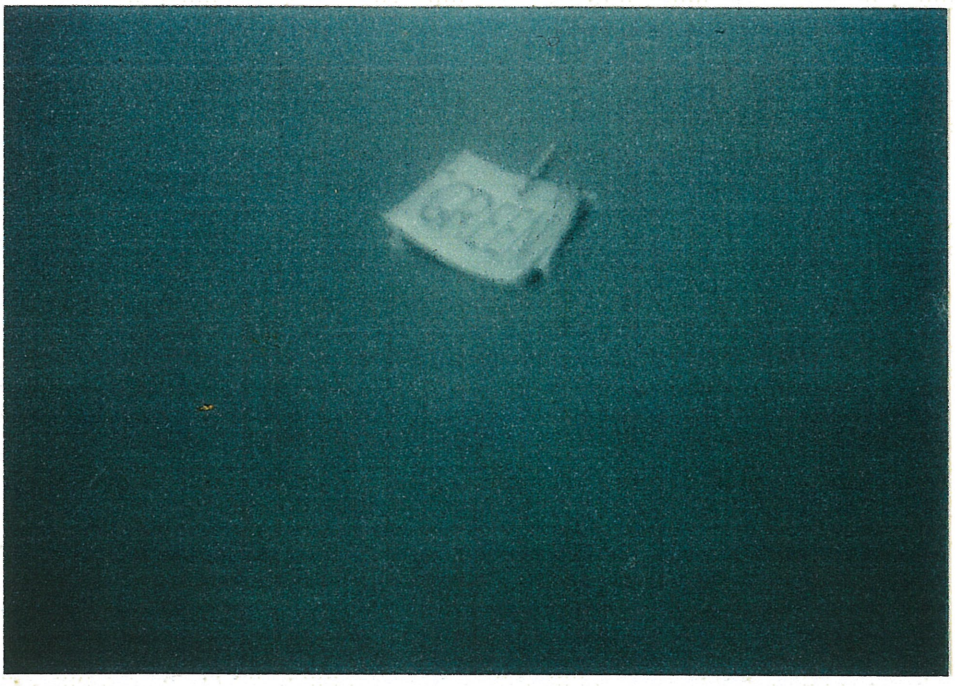


Plate 4 Green net:- (mean diver visual range = 3.1m)

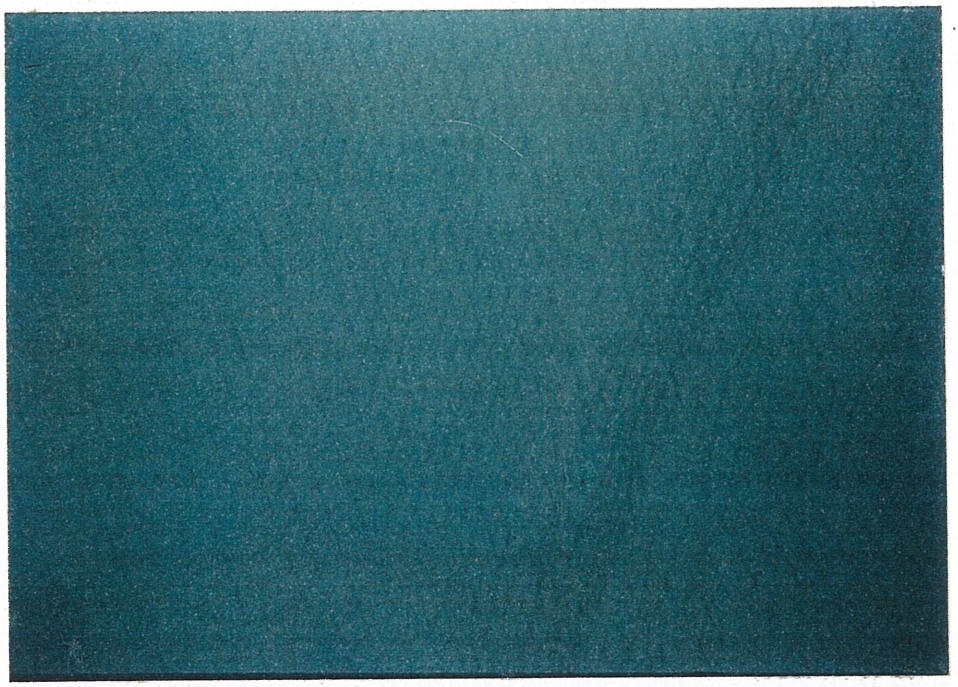


Plate 5 Black net:- (mean diver visual range = 4.55m)

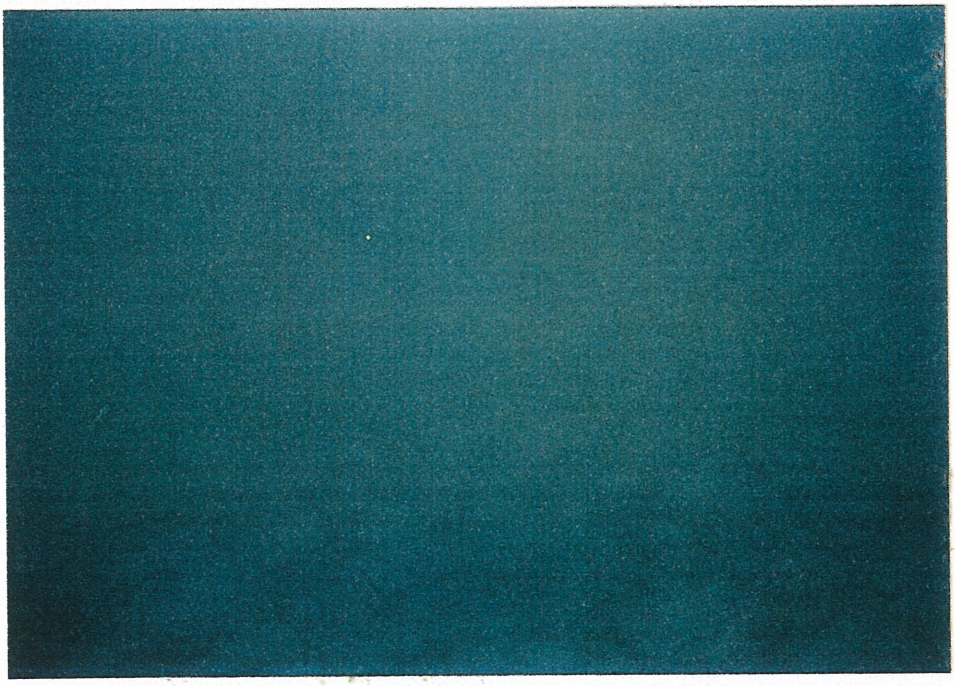


Plate 6 Yellow net:- (mean diver visual range = 3.5m)

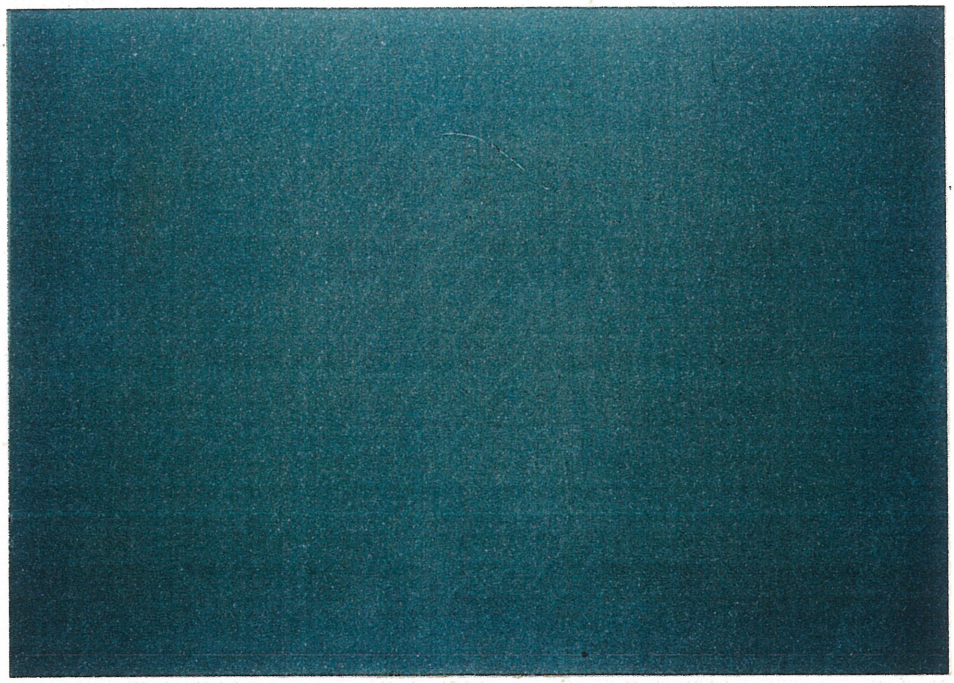


Plate 7 White net:- (mean diver visual range = 4.4m)

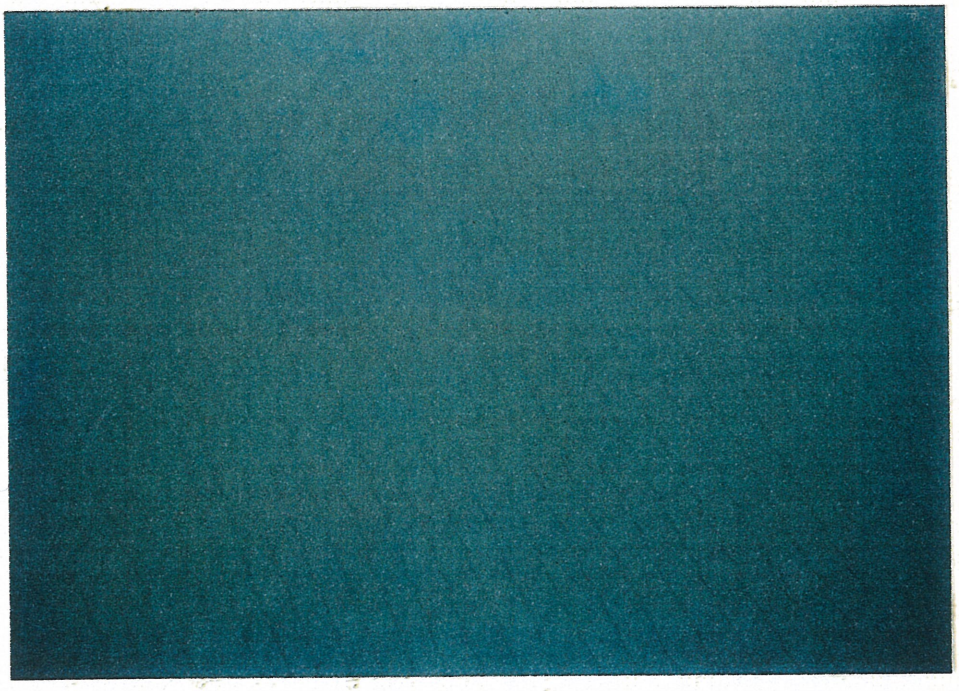


Plate 8 Red net:- (mean diver visual range = 5.05m)

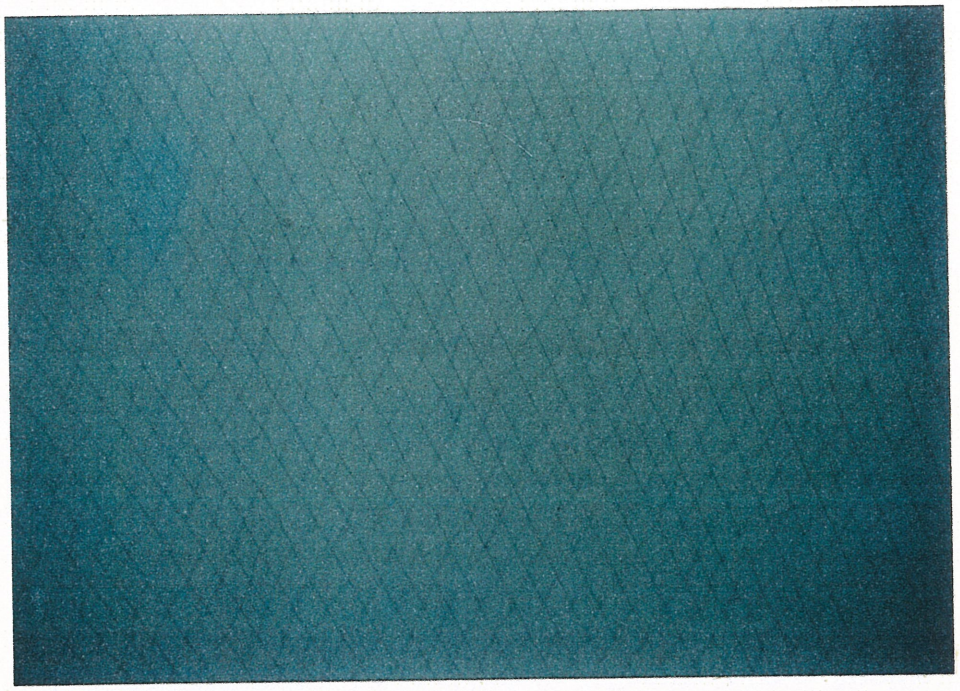


Plate 9 Brown net:- (mean diver visual range = 5.0m)

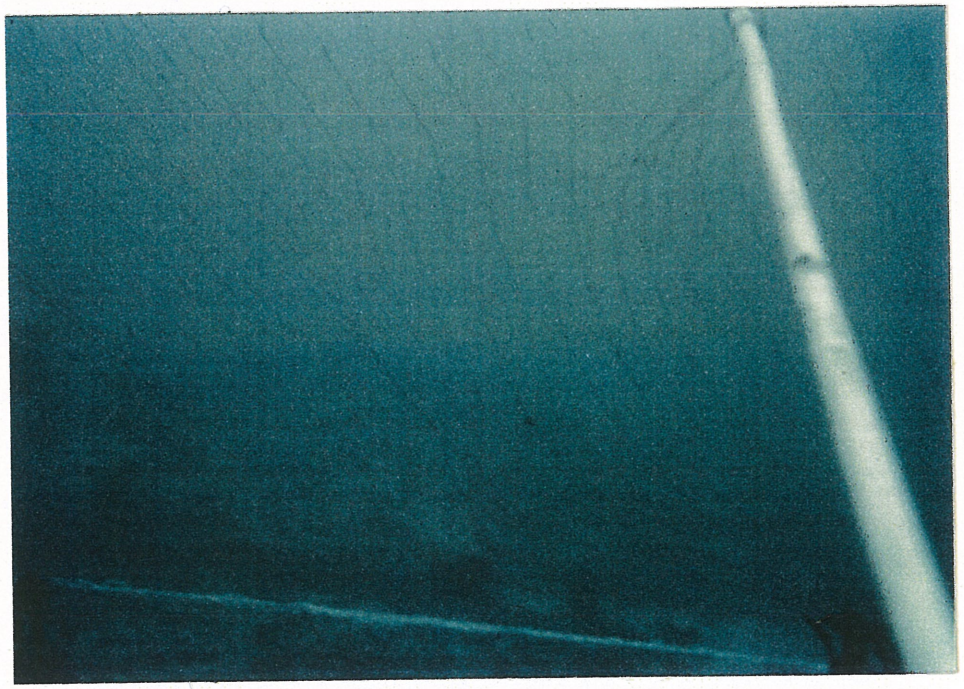


Plate 10 Grey net:- (mean diver visual range = 3.45m)

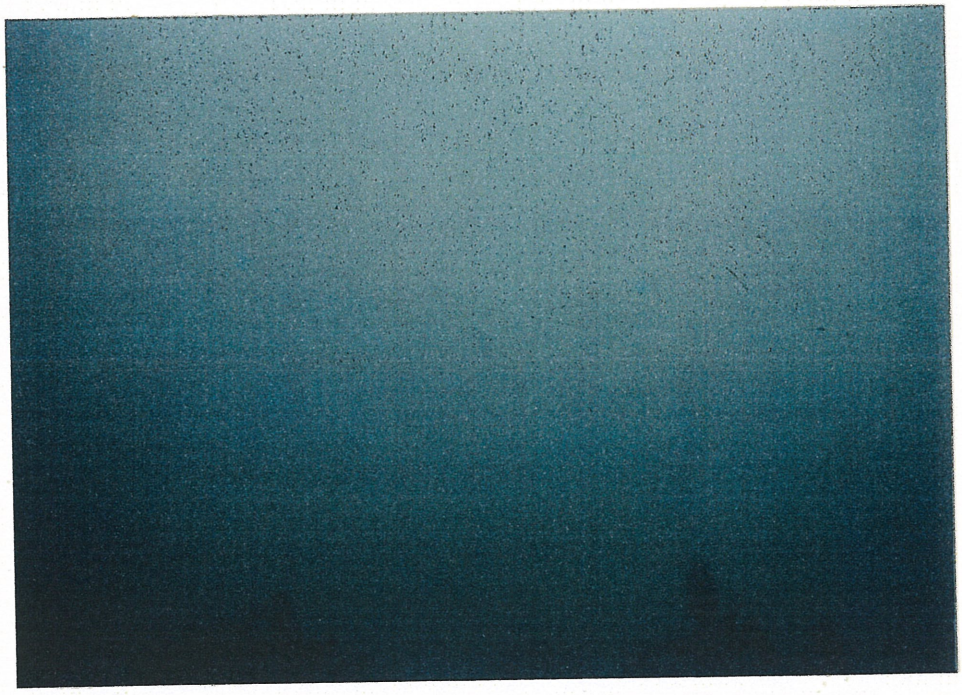


Plate 11 Monofilament: (mean diver visual range = 2.7m)
(Used for comparison with coloured nets)

Table 13

DATE 30th – 31st / 1 / 81 SITE PEADER ROCK, WEST OF RAME HEAD. DEPTH 14 m.

TIME SET 16-45 TIME HAULED 0815 TIME FISHED 15 hr 30 min

SECCHI DISC DEPTH 1) 8·85 m. 2) 10·05 m. AV. 9·45 m.

% TRANSMITANCE AT NET DEPTH 1) NOT AVAILABLE 2) ____ AV. ____

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
POLLACK	2	1	4	3	6	2		2	20
COD				1					1
POOR COD								2	2
POUT					1		1		2
(EDIBLE CRAB)					(1)				(1)
Total in each net	2	1	4	4	7 (1)	2	1	4	Total Catch = 25 fish

Sea State:- Calm/~~Rough~~ Average Surface Irradiance/hour fished ___ mW

Wind: SE 1. Sky:- Overcast/~~Cloudy/Clear~~ [FOG]

Comments: BOTTOM; ROCKS AND SAND. 2 POLLACK HAD BEEN EATEN BY CRABS.

NOTE: FISHED OVER NIGHT.

Table 14

DATE 28-29th/4/81 SITE TINKER Buoy DEPTH 16m

TIME SET 10-30 TIME HAULED 09-30 TIME FISHED 23 hr.

SECCHI DISC DEPTH 1) 11m 2) ____ AV. 11m

% TRANSMITANCE AT NET DEPTH 1) ____ 2) ____ AV. NOT AVAILABLE

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
POLLOCK						1		3	4
BALLAN WRASSE					1	3	3	1	8
3-BEARDED - ROCKLING	1								1
CUCKOO WRASSE					1				1
DOGFISH (LESSER SPOTTED)				2					2
Total in each net	1	0	0	2	2	4	3	4	Total Catch = 16 fish

Sea State:- Calm/~~Rough~~ Average Surface Irradiance/hour fished ___ mW

Wind: N-ly 2 Sky:- Overcast/~~Cloudy/Clear~~

Comments: WATER is HEAVILY LADDEN WITH PLANKTON, OTHERWISE CLEAR, Nets all brown with plankton. Bottom thought to be shale or smooth rocks.

Table 15

DATE 29th - 30th /4/81 SITE SOUTH OF BREAKWATER DEPTH 16 m

TIME SET 1100 TIME HAULED 1600 TIME FISHED 29 hours

SECCHI DISC DEPTH 1) 8m 2) 9m AV. 8·5m

HORIZONTAL DISTANCE, BLACK BODY AT NET DEPTH 1) 2) AV.

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
BALLAN WRASSE	2	1		1	1			3	8
POLLOCK	2		1		1	1		1	6
CUCKOO WRASSE		1							1
DOGFISH (LESSER SPOTTED)	3			2			1		6
Total in each net	7	2	1	3	2	1	1	4	Total Catch = 21 fish

Sea State:- Calm/~~Rough~~ Average Surface Irradiance/hour fished ___ mW

Wind: NW 4-5 Sky:- ~~Overcast~~/Cloudy/~~Clear~~

Comments: BOTTOM :- shale, boulders and reef, Net hung up along it's length. Lobster observed eating wrasse in the net without being caught. Lot of plankton in water and colouring nets brownish.

DATE 1st – 3rd /5/81 SITE JENNYCLIFF BAY DEPTH 10 m

TIME SET 17-30 TIME HAULED 10-00 TIME FISHED 40 hr 30 min.

SECCHI DISC DEPTH 1) _____ 2) _____ AV. NOT AVAILABLE

% TRANSMITANCE AT NET DEPTH 1) _____ 2) _____ AV. NOT AVAILABLE

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
BALLAN WRASSE							2	1	3
POUT								1	1
Total in each net	0	0	0	0	0	0	2	2	Total Catch = 4 fish

Sea State:- Calm/~~Rough~~ Average Surface Irradiance/hour fished _____ mW

Wind: W -> SW 4-5 Sky:- Overcast/Cloudy/~~Clear~~

Comments: Water CLEAR – VISIBILITY GOOD.
NET FULL OF RUBBISH:- TREE ROOTS, BRANCHS, KELP ROOTS, TIN CAN, CRABS, etc.
WHITE NET VERY DAMAGED.
BOTTOM PROBABLY MUD AND SHINGLE.

Table 17

DATE 5-6/5/81 SITE JUST SOUTH OF BREAKWATER LIGHTHOUSE DEPTH 16 m.

TIME SET 11-30 TIME HAULED 10-00 TIME FISHED 22hr 30 min

SECCHI DISC DEPTH 1) _____ 2) _____ AV. NOT AVAILABLE.

% TRANSMITANCE AT NET DEPTH 1) _____ 2) _____ AV. NOT AVAILABLE

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
POLLOCK	11	4	3	1	2	3	1		25
CUCKOO WRASSE	1		1						2
LING	1								1
POUT			1						1
								FOULED	
								NET	
Total in each net	13	4	5	1	2	3	1		Total Catch = 29 fish

Sea State:- Calm/~~Rough~~ – SE. SWELL. Average Surface Irradiance/hour fished ___ mW

Wind: SW 4 Sky:- Overcast/~~Cloudy/Clear~~

Comments: VISIBILITY GOOD; SECCHI DISC WOULD PROBABLY BE ABOUT 10m+. BOTTOM SHINGLE AND SAND, LITTLE WRECKAGE IN NETFOOTROPE. BLUE NET TOTALLY FOULED UP; PARTIALLY WITH RED NET.

Table 18

Depth: Shallow (14, 16, 16, 10, 16m)

Water: Clear (Secchi disc depth = 9.45, 11, 8.5, -, -)

	Brown	Black	Grey	Red	Green	Yellow	Blue	White	Total
	1	2	2	4	1	7	4	4	25
	0	4	1	0	3	2	4	2	16
	2	1	7	1	1	2	4	3	21
	0	0	0	0	2	0	2	0	4
	4	3	13	5	1	2	(11)	1	29+11
Total catch	7	10	23	10	8	13	25	10	106
Proportion of catch	0.066	0.094	0.217	0.094	0.075	0.123	0.236	0.094	
1- prop. of catch	0.934	0.906	0.783	0.906	0.924	0.877	0.764	0.906	

The bracketed blue value has been obtained from the mean proportion in the blue net, in 4 previous cases, i.e. 27.5% of the catch.

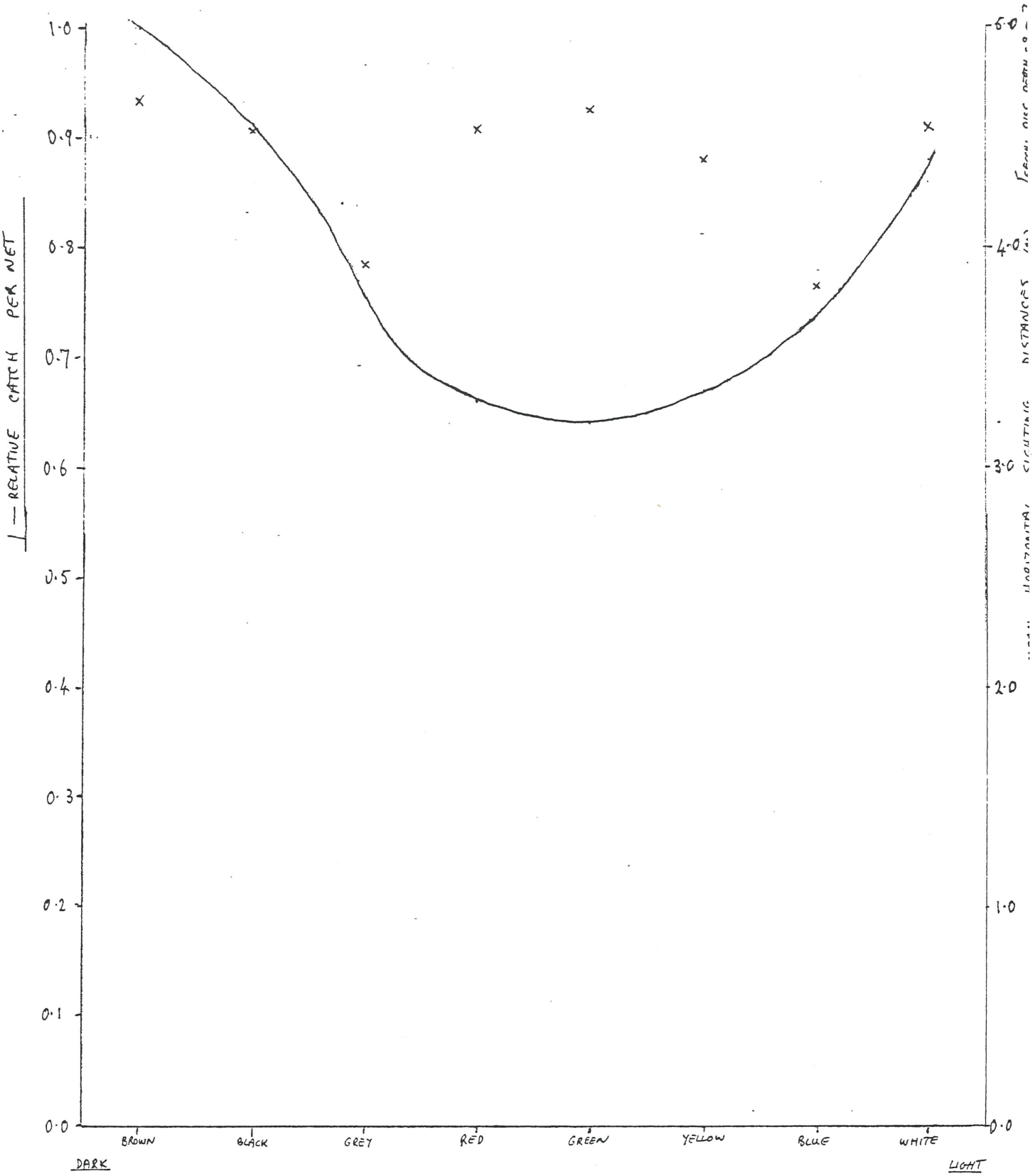
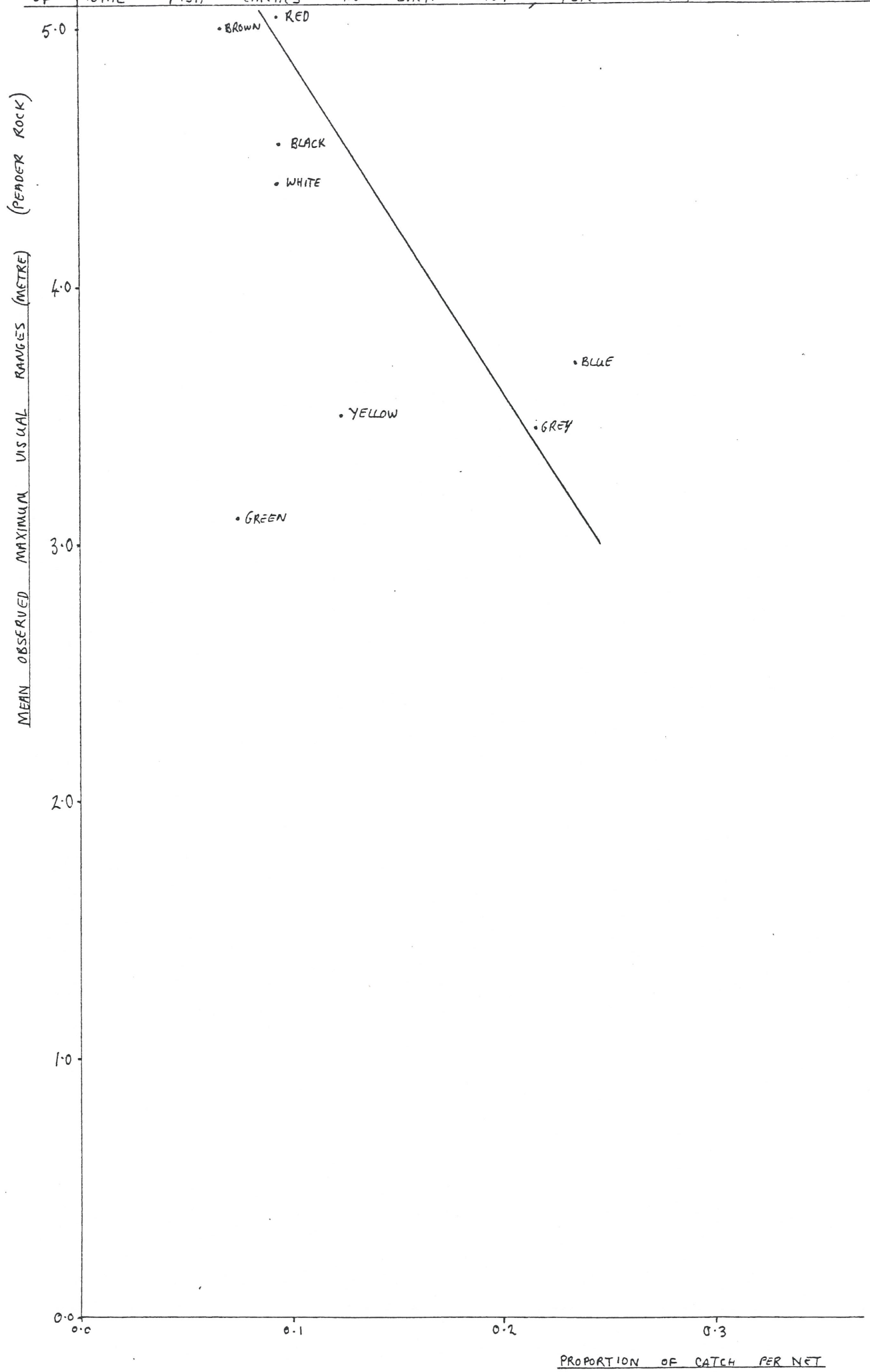


Fig 29 :- RESULTS FROM FISHING AT DEPTHS FROM 10 – 16 m IN PLYMOUTH AREA (SECCHI DISC DEPTH = 9·45, 11, 8·5, AND 2 OCCASION WHEN NOT AVAILABLE) ON 30-31/1, 28-29/4, 29-30/4, 1-3/5 AND 5-6/5.

Nº OF TIMES FISHED = 5 ; TOTAL Nº OF FISH CAUGHT = 95 (INCLUDING 8 DOGFISH.)

A SCATTER DIAGRAM OF DIVER OBSERVED VISUAL RANGES AGAINST PROPORTION OF TOTAL FISH CATCHES IN EACH NET ; FOR SIMULAR WATER CONDITIONS



Calculation of Correlation Coefficient (r) for catches (X) to the observed visual ranges (Y) in clear water

	Brown	Black	Grey	Red	Green	Yellow	Blue	White	
Proportion of catches (X)	0.066	0.094	0.217	0.094	0.075	0.123	0.236	0.094	=
	Total 1.00 = ΣX								
Visual ranges (Y)	5.00	4.55	3.45	5.05	3.10	3.50	3.70	4.40	=
	Total 32.75 = ΣY								
X^2	0.0044	0.0088	0.0471	0.0088	0.0056	0.0151	0.0557	0.0088	=
	Total 0.154 = ΣX^2								
Y^2	25.0	20.7	11.9	25.5	9.61	12.25	13.69	19.36	=
	Total 138.02 = ΣY^2								
X Y	0.33	0.4277	0.749	0.475	0.233	0.431	0.873	0.414	=
	Total 3.933 = ΣXY								

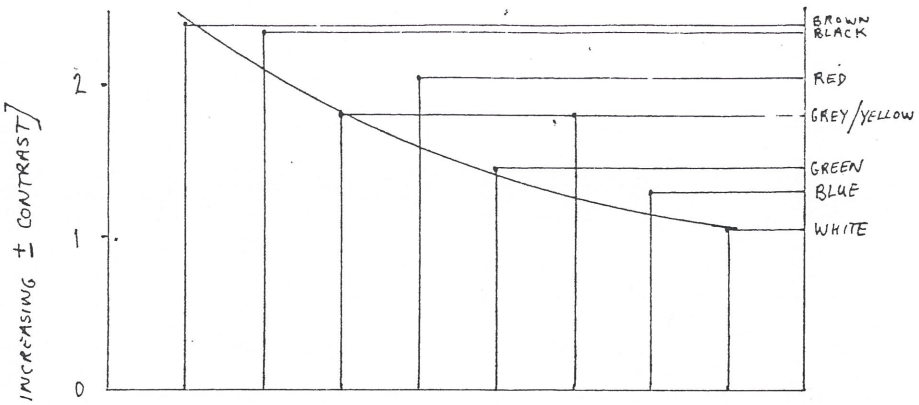
$$r = \frac{3.933 - (1.0 \quad 32.75)/8}{\sqrt{(0.154 - 1^2/8)(138.02 - 32.75^2/8)}}$$

$$r = \frac{-0.16075}{\sqrt{(0.029)(3.949)}} = \frac{-0.16075}{0.338} = \underline{-0.476}$$

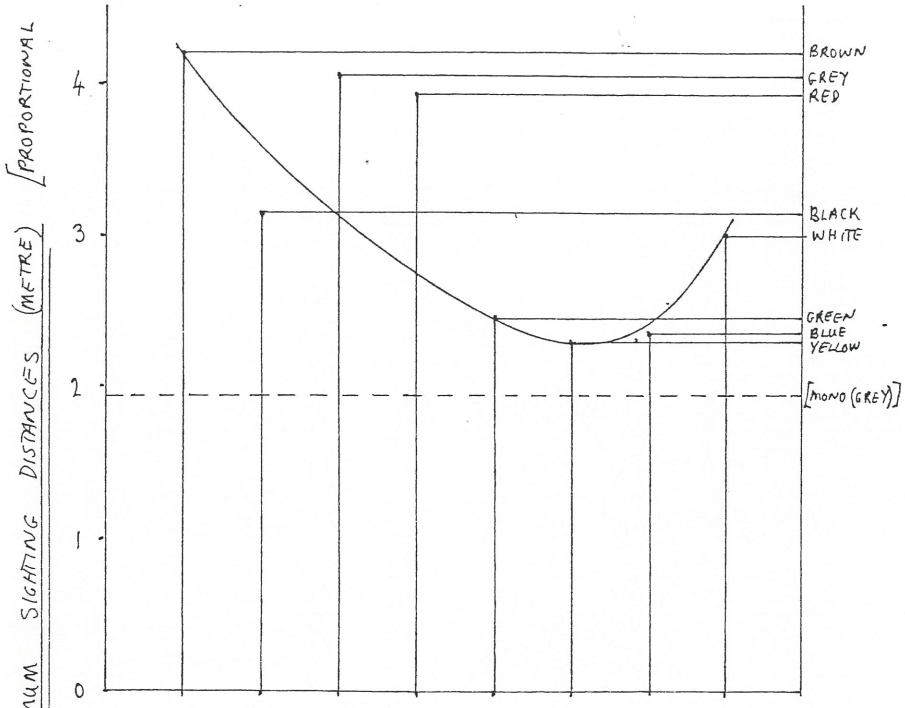
This value suggests a slight negative relationship, i.e. the higher the observed net visibility the less it catches.

See Fig. 31 for plots of mean diver observed sighting distances (metres) against net colours in order of brightness; as obtained from photographs taken at Peader Rock. For each of the 3 designated water clarity conditions as used in analysis of the results of fishing in Plymouth Sound area at a depth of about 14m.

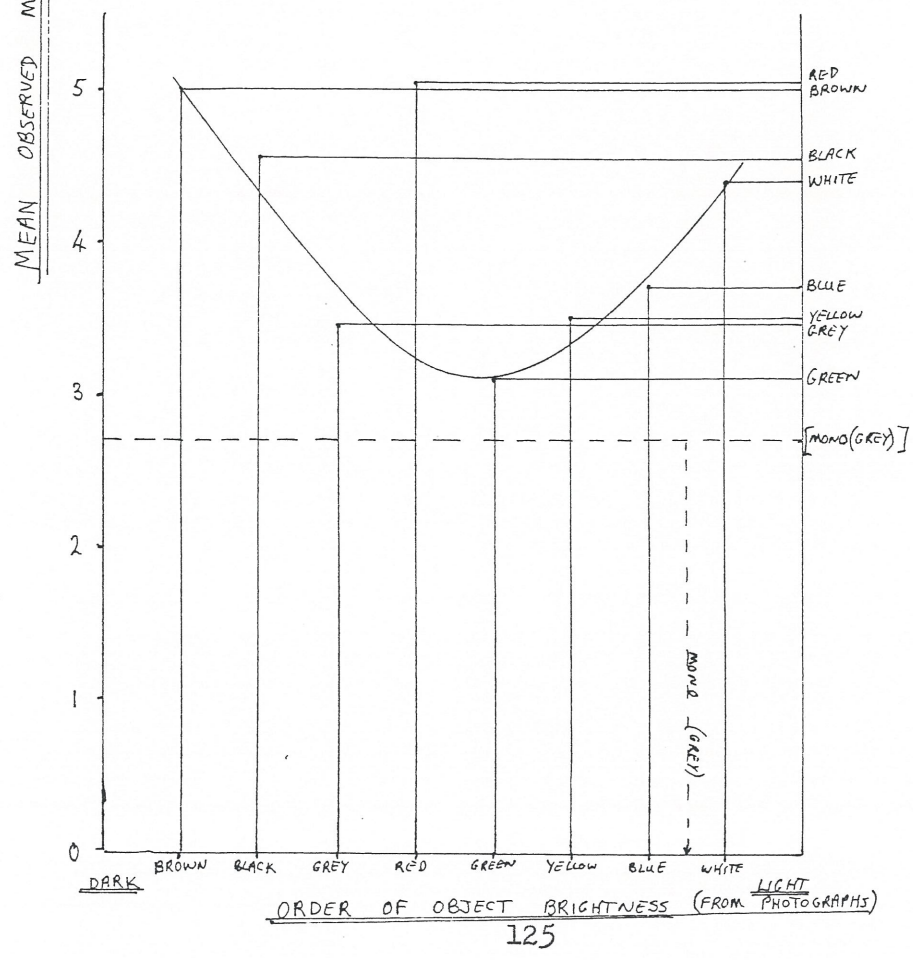
J.9 CONTRAST BETWEEN NET COLOUR AND BACKGROUND IN WATERS OF DIFFERENT ATTENUATION PROPERTIES



a) DUKE ROCK: 7/4/81
DEPTH = 15m.
$\mathcal{L}_c = 0.88m$; $\mathcal{L}_K = 2.36m$
AS THE WATER IS TURBID VISUAL RANGES ARE LOW, AND THE LOWEST CONTRAST IS WITH A VERY LIGHT COLOUR i.e. TENDING TOWARDS WHITE.



b) CAWSAND BAY: 7/2/81
DEPTH = 14m : SECCHI DISC = 3 m.
$\mathcal{L}_c = 1.49m$; $\mathcal{L}_K = 3.97m$.
WITH THE WATER BEING CLEARER VISUAL RANGES INCREASE. ALSO AS SCATTERANCE IS REDUCED THE BACKGROUND APPEARS DARKER.
THE OPTIMUM IS NOW YELLOW WITH BLUE AND GREEN BEING SLIGHTLY MORE VISIBLE.
THE LOW CONTRAST WITH THE YELLOW IS PROBABLY DUE TO IT'S BRIGHTNESS RATHER THAN COLOUR.



c) PEADER ROCK: 21/2/81.
DEPTH = 14m : SECCHI DISC = 9.5m.
$\mathcal{L}_c = 1.87m$; $\mathcal{L}_K = 5.00m$.
THE WATER IS CLEAR WITH HIGH VISUAL RANGES. DUE TO THE "HIGH" TRANSPARENCY OF THE WATER THE OPTIMUM COLOUR NET BECOMES DARKER ie GREEN, WITH GREY AND YELLOW AS A CLOSE SECOND.

[RED, IS APPARENTLY DARKER THAN OBSERVED FROM PHOTOGRAPHS. MONOFILAMENT, BEING TRANSPARENT ALWAYS HAS THE LOWEST VISUAL RANGE BUT TENDS TO BE BRIGHTER THAN OPTIMUM DUE TO NET SURFACE REFLECTION.]

Waters adjacent to Plymouth Sound at an approximate depth of 30m.

1. Clear water (Secchi disc depth > 9.5m)

- Diver observation (west of Mew Stone)

  Table of results (see Table 19) and graphical plot (see Fig. 32)

  Plot of diver observation ranges against net colours in order of brightness (determined in 14m) (see Fig. 33)

- Fishing results

  Tables of results (2) (see Tables 20 and 21)

  Calculations of proportion of total fish in each net and for teleost fish only in each net (see Table 22)

  Plot of 1- relative proportion of total catch and diver observed ranges against colours of nets; in order of brightness (as determined in 14m depth) (see Fig. 34)

- Analysis

  Scatter diagram of mean diver observed ranges against proportion of catch for each net colour with and without Elasmobranch (see Fig. 35)

  Calculation of correlation coefficient for above plots

Table 19

DATE 1/5/81 SITE WEST OF MEWSTONE DEPTH 31m

TIME SET 17-30 on 30th of April. TIME HAULED 1500 TIME FISHED 21 hr 30 min

SECCHI DISC DEPTH 1) ... 2) ... AV. NOT AVAILABLE

HORIZONTAL BLACK BODY DISTANCE ; AT NET DEPTH 1) ... 2) ... AV. ESTIMATED AT ≈ 6m. †

Net Colour / HORIZONTAL RANGE (m)	Grey	Brown	Red	White	Yellow	Black	Green	Blue	OBSERVER'S INITIALS
			3·1	2·9			2·9	2·6	S. M.
	3·0	3·3		2·9	4·1	4·0			P. H
MEAN RANGES (m)	3·0	3·3	3·1	2·9	4·1	4·0	2·9	2·6	
ORDER OF INCREASING VISUAL RANGE ≡ INCREASING ± CONTRAST	4	6	5	2	8	7	2	1	

Sea State:- Calm/~~Rough~~ Average Surface Irradiance/hour fished ___ mW

Wind: N'ly 3 Sky:- ~~Overcast~~/Cloudy/~~Clear~~

Comments: OBSERVATIONS WERE MADE PRIOR TO HAULING AFTER 21½ HOURS FISHING. — SEE CATCH FIGURES FOR 30-1/5/81.
DESPITE THICK SURFACE PLANKTON BLOOM; AT NET DEPTH VIS WAS GOOD AND AVAILABLE LIGHT LEVELS WERE HIGH.
ALL MESHES WERE THICKLY COVERED IN FILAMENTS OF PLANKTON WHICH INCREASED THEIR VISIBILITY, NET COLOURS WERE JUST DIFFERENTIABLE WITH THE HUMAN EYE. THOUGH THEY ALL LOOKED PRETTY MUCH THE SAME; WITH THE EXEPTION OF BLUE AS WOULD BE EXPECTED AT THIS DEPTH.
BOTTOM WAS FLAT ROCK AND SHINGLE WITH SHALLOW LEDGES.

MAXIMUM HORIZONTAL DISTANCE AT WHICH, EACH COLOUR NETTING COULD BE SEEN BY EACH DIVER (INDICATED BY INITIALS), AT 31 m DEPTH WEST OF THE MEW STONE. BLACK BODY DISTANCE WAS NOT MEASUED THEREFORE NO VALUES OF ATTENUATION COEFFICIENT OR LENGTHS ARE AVAILABLE. BLACK BODY DISTANCE WAS PROBABLY IN EXCESS OF 6 m.

(DATE: 1/5/81)

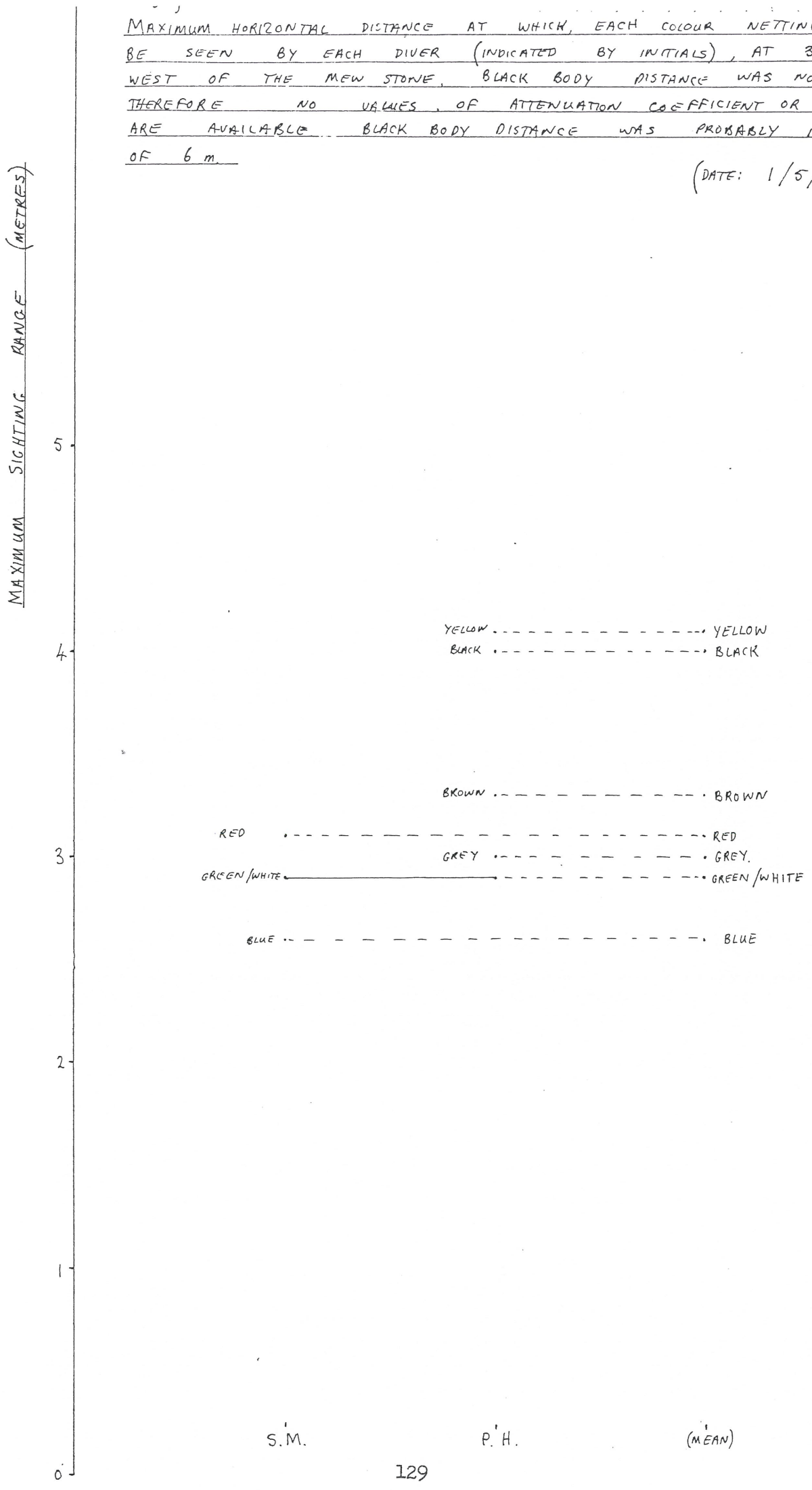
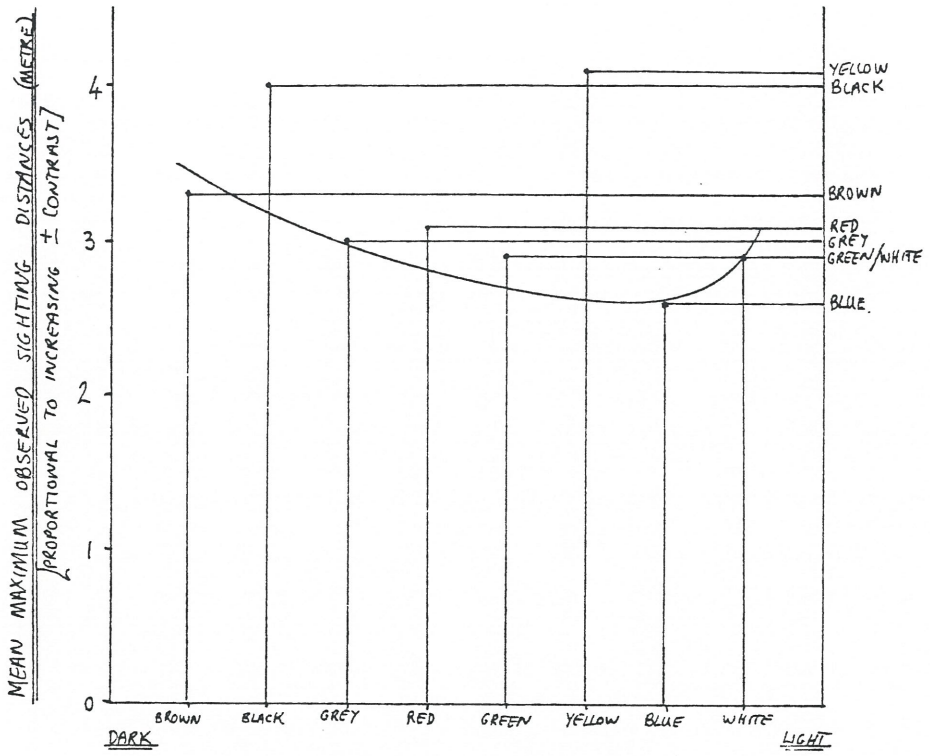


fig 33 :

CONTRAST BETWEEN NET COLOUR AND WATER BACKGROUND ; AT DEPTH OF 31m. WEST OF THE MEWSTONE. : 1/5/81.



ORDER OF BRIGHTNESS OBSERVED AT 14m.

DUE TO DEPTH OF WATER, GET ONLY LIGHT OF BLUISH-GREEN WAVELENGTHS AS THESE HAVE BEEN ABSORBED LEAST. THUS AT THIS DEPTH THE AVAILABLE LIGHT IS BLUISH AND OF REDUCED INTENSITY WHEN COMPARED WITH THE SURFACE. WITH THE LIMITED SPECTRUM AND PLANKTON IN THE WATER AND ON THE MESHES. THE NETS TEND TO HAVE SIMULAR APPARENT COLOURS AND VISUAL RANGES. THE MAIN EXCEPTIONS BEING YELLOW AND BLACK WHICH ARE VERY CONSPICUOUS. BLUE AS WOULD BE EXPECTED HAS VERY LOW CONTRAST AND IS THEREFORE LEAST VISIBLE. OTHER LESS VISIBLE COLOURS INCLUDE GREEN AND WHITE; GREEN TENDING TO CONTRAST WEAKLY WITH THE WATER BACKGROUND, AND WHITE BY ITS NATURE REFLECTS ALL AVAILABLE WAVELENGTHS ie. BLUISH.

THE ORDER OF BRIGHTNESS ILLISTRATED IS FOR NETS PHOTOGRAPHED IN CLEAR WATER AT 14m. DEPTH. THE ACTUAL ORDER AT 31m DEPTH WILL PROBABLY ALTER; ESPECIALLY FOR SUCH COLOURS AS YELLOW AND RED, AS THE WAVELENGTHS WHICH COMPOSE THESE COLOURS WILL BE REDUCED IN AVAILABILITY, THUS THEY TEND TOWARDS BEING BLACK ie. DARKER.

PHOTOGRAPHIC EVIDENCE FROM THIS DEPTH IS NOT AVAILABLE AS THE UNDERWATER CAMERA WAS BEING USED ELSE WHERE.

TABLE 20

DATE 24th/1/81 SITE HILSEA POINT DEPTH 28 m.

TIME SET 0830 TIME HAULED 1645 TIME FISHED 8hr 15 min

SECCHI DISC DEPTH 1) 11.25 m 2) 8.25 m AV. 9.75 m

% TRANSMITANCE AT NET DEPTH 1) NOT AVAILABLE 2) _____ AV. _____

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
POLLOCK	1				2				3
BALLAN WRASSE	1								1
Total in each net	2	0	0	0	2	0	0	0	Total Catch = 4 fish

Sea State:- Calm/~~Rough~~ Average Surface Irradiance/hour fished ___ mW

Wind: W. 1-2 Sky:- Overcast/~~Cloudy/Clear~~

Comments: BOTTOM ROCKY. SEVERAL DEAD MAN'S FINGERS (ALCYONIUM DIGITATUM) HUNG IN NETS.

NOTE: FISHED DURING DAYLIGHT HOURS. HAULED JUST BEFORE DUSK.

THE WRASSE WAS NOTICEABLY LIGHTER COLOURED THAN THOSE CAUGHT IN THE BLUE NET ON 4th/12/80 IN COMPARITIVELY SHALLOW WATER (7m); WHEN FISHED OVERNIGHT.

Table 21

DATE 30-1/5/81 SITE WEST OF MEWSTONE DEPTH 31 m.

TIME SET 17-30 TIME HAULED 15:00 TIME FISHED 21 hr 30 min

SECCHI DISC DEPTH 1) ____ 2) ____ AV. NOT AVAILABLE

% TRANSMITANCE AT NET DEPTH 1) ____ 2) ____ AV. NOT AVAILABLE

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
BALLAN WRASSE	2	1	3	0	6	1	6	3	22
POLLOCK	0	0	0	0	2	0	0	0	2
ROUT	4	1	0	0	0	0	0	4	9
CUCKOO WRASSE	2	0	1	0	1	1	1	0	6
DOGFISH (LESSER SPOTTED)	2	1	8	3	2	11	6	1	34
Total in each net	10	3	12	3	11	13	13	8	Total Catch = 73 fish

Sea State:- Calm/~~Rough~~ Average Surface Irradiance/hour fished ___ mW

Wind: N'ly 3 Sky:- ~~Overcast~~/Cloudy/~~Clear~~

Comments: NETS WERE DIVED ON PRIOR TO HAULING, LOT OF PLANKTON IN UPPER WATER MASS; BUT LESS THICK ON BOTTOM. VISIBILITY WAS APPROXIMATELY 6m+ WITH GOOD LIGHT PENETRATION FROM SURFACE. BOTTOM; shingle and flat rock with low ledges. SET ACCROSS TIDE.

ORDER OF NETS :- WHITE, BROWN, YELLOW, BLACK, GREY, GREEN, RED, BLUE

SEE DIVER OBSERVATIONS FOR THIS SETTING :- NO APPARENT CORRELATION BETWEEN DIVER OBSERVED VISIBILITY OF EACH NET AND CATCHES MADE IN EACH.

Table 22

Depth: Deep (28m, 31m)

Water: Clear (Secchi disc depth 9.75m, -)

	Brown	Black	Grey	Red	Green	Yellow	Blue	White	Total
	0	0	2	0	0	2	0	0	4
	3	13	10	12	13	11	8	3	73
Total catch	3	13	12	12	13	13	8	3	77
Proportion of catch	0.039	0.169	0.156	0.156	0.169	0.169	0.104	0.03	
1- prop. of catch	0.961	0.831	0.844	0.831	0.831	0.831	0.896	0.961	

Without Elasmobranchs (Dogfish) (T) i.e. teleost fish only

	Brown	Black	Grey	Red	Green	Yellow	Blue	White	Total
	0	0	2	0	0	2	0	0	4
	2	2	8	4	7	9	7	0	39
Total	2	2	10	4	7	11	7	0	43
Proportion of catch	0.046	0.046	0.233	0.093	0.163	0.256	0.163	0.0	
1- prop. of catch	0.953	0.953	0.767	0.907	0.837	0.744	0.837	1.0	

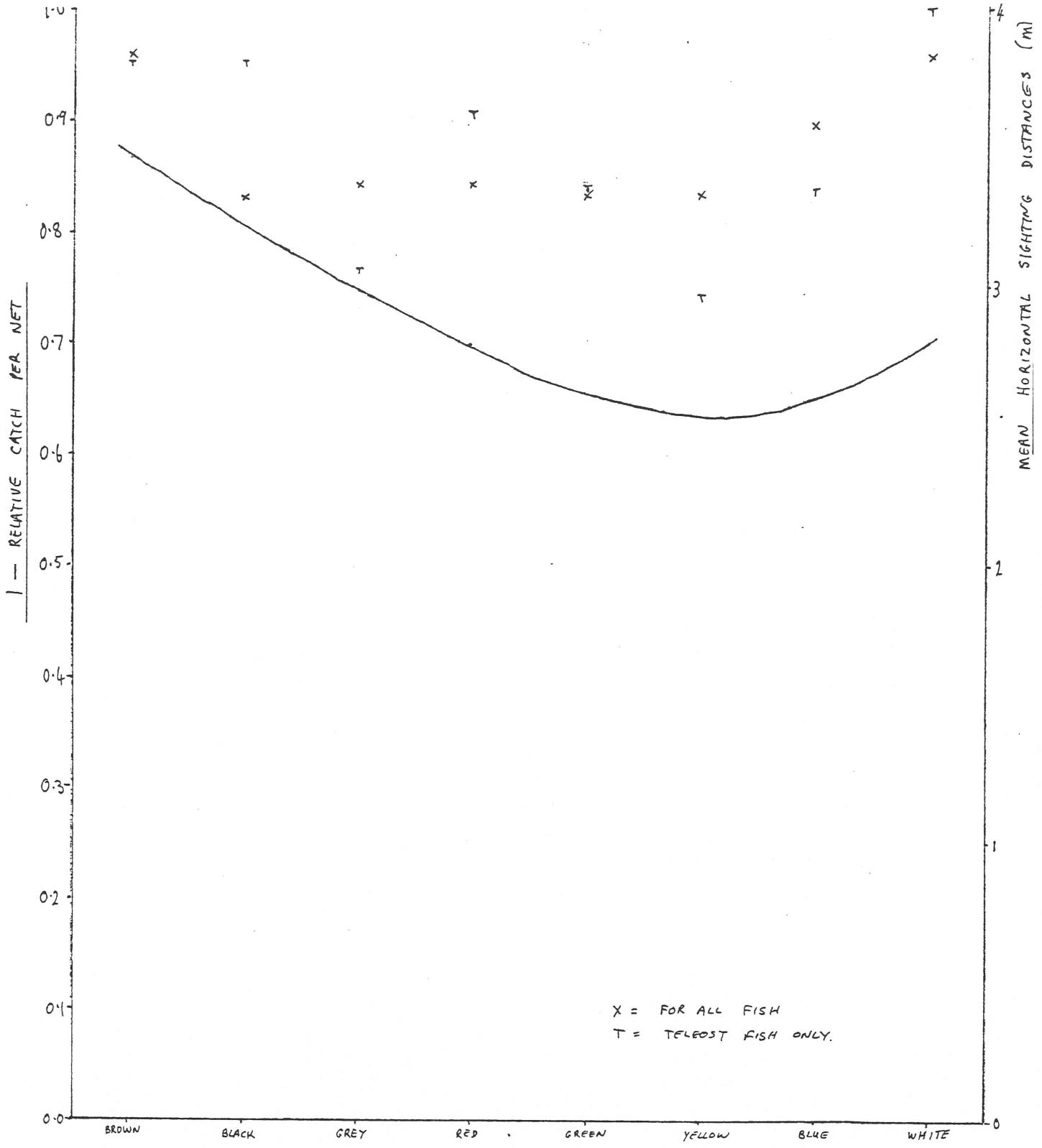


fig 34: RESULTS FROM FISHING DEEP WATER; 28 AND 31m. ON 24/1 AND 30-1/5.

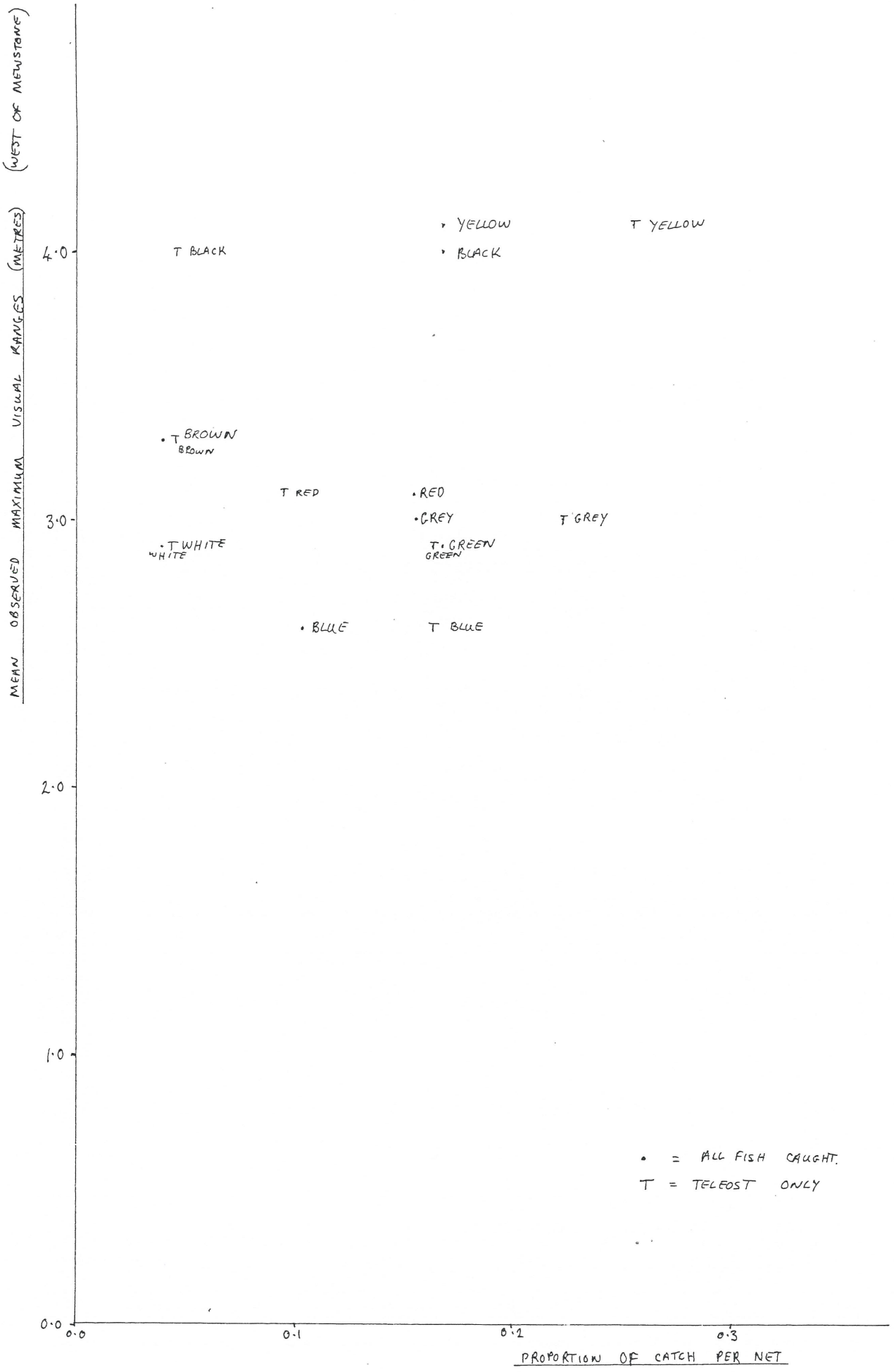
Nº OF TIMES FISHED = 2 TOTAL Nº OF FISH CAUGHT = 77 (including 34 dogfish)

CATCHES IN RED, WHITE AND BLACK ALMOST EXCLUSIVELY ELASMOBRANCHS (DOGFISH); WHICH HAVE ONLY SCOTOPIC VISION. RAY NETS TRADITIONALLY BLACK. BIGGEST CATCHES OF DOGFISH WERE BY THE BLACK NET; WITH RED SECOND.

REMOVAL OF THE ELASMOBRANCH CATCH DATA HAS LITTLE EFFECT UPON THE ABOVE GRAPH; EXCEPT THE WHITE NET GOES TO ZERO CATCH.

THE FACT THAT YELLOW WAS CONSISTANTLY TOP NET COMES AS A SURPRISE AS DIVER OBSERVATIONS PUT IT AS THE MOST VISIBLE. SIMULARLY WHITE CAUGHT ONLY 3 DOGFISH IN TOTAL BUT DIVERS PUT IT AS EQUAL SECOND LEAST VISIBLE; WITH GREEN — CAUGHT EQUAL MOST ON SECOND SET.

A SCATTER DIAGRAM OF DIVER OBSERVED VISUAL RANGES AGAINST PROPORTIONS OF THE TOTAL FISH CATCHES IN EACH NET : FOR SIMILAR WATER CONDITIONS



Calculation of Correlation Coefficient (r) for catches (X) against observed visual ranges (Y); in clear water at approx. 30m.

	Brown	Black	Grey	Red	Green	Yellow	Blue	White	
Proportion of catches (X)	0.039	0.169	0.156	0.156	0.169	0.169	0.104	0.0389	=
	Total 1.00 = ΣX								
Visual ranges (Y)	3.3	4.0	3.0	3.1	2.9	4.1	2.6	2.9	=
	Total 25.9 = ΣY								
X^2	0.0015	0.0286	0.0243	0.0243	0.0286	0.0286	0.0108	0.0015	=
	Total 0.1482 = ΣX^2								
Y^2	10.89	16.0	9.0	9.61	8.41	16.81	6.76	8.41	=
	Total 85.89 = ΣY^2								
X Y	0.1287	0.676	0.468	0.484	0.490	0.693	0.270	0.1128	=
	Total 3.3225 = ΣXY								

$$r = \frac{3.325 - (1.00 \quad 25.9)/8}{\sqrt{(0.1482 - (1)^2/8)(85.89 - (25.9)^2/8)}}$$

$$\frac{0.085}{\sqrt{(0.0232)(2.0387)}} = \frac{0.085}{0.2175} = \underline{0.391}$$

This value suggests a possible positive correlation, i.e. the more visible a net the higher is its catch. In this case yellow is observed to be most visible and also catches most fish including or excluding elasmobranchs.

Recalculating with all elasmobranchs, i.e. dogfish removed from results.

	Brown	Black	Grey	Red	Green	Yellow	Blue	White
Proportion of catches (X^1)	0.046	0.046	0.233	0.093	0.163	0.256	0.163	0.0 =
	Total 1.00 = ΣX							
X^2	0.0021	0.0021	0.053	0.00865	0.0266	0.0655	0.0266	0.0 =
	Total 0.1858 = ΣX^2							
X Y	0.1518	0.184	0.699	0.288	0.473	1.0496	0.424	0.0 =
	Total 3.269 = ΣXY							

$$r = \frac{3.269 - (1.0 \times 25.9)/8}{\sqrt{(0.1858 - (1)^2/8)(85.89 - (25.9)^2/8)}}$$

$$= \frac{0.0315}{\sqrt{(0.0608)(2.0387)}} = \frac{0.0315}{0.352} = \underline{0.089}$$

This suggests virtually no correlation, i.e. random catches for teleost fish.

Additional results:-

Christchurch Bay area with nets surface rigged

1. Very low visibility water (Secchi disc < 2.75m)

- Fishing results

Tables of results (4) (see Tables 23-26)

Calculation of proportion of total catch, in each net (see Table 27)

Plot of 1- relative proportion of catch, and diver observed ranges ranges against colours of nets; in order of brightness (see Fig. 36)

Table 23

DATE 8th - 9th / 9 / 80 SITE OFF SOUTHBOURNE BEACH BOURNEMOUTH BAY, DORSET. DEPTH 10 m.

TIME SET 20-00 TIME HAULED 07-30 TIME FISHED 11 hr 30 min.

SECCHI DISC DEPTH 1) 2·75 m. 2) ____ AV. 2·75 m.

% TRANSMITANCE AT NET DEPTH 1) ____ 2) ____ AV. ____

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
MACKEREL		1		2		1	1	1	6
HORSE MACKEREL								2	2
MULLET			1						1
Total in each net	0	1	1	2	—	1	1	3	Total Catch = 9 fish

YELLOW: NOT FISHED DUE TO BEING FOULED WITH ANCHOR DURING SETTING. (WAS REMOVED FROM FLEET).

Sea State:- Calm/~~Rough~~ Average Surface Irradiance/hour fished ___ mW

Wind: W. 3-4. Sky:- ~~Overcast/Cloudy~~/Clear

Comments: VERY STRONG SPRING TIDE. NETS SURFACE RIGGED ON BUOYS 1m ABOVE HEAD-LINE. NETS HELD WITH ANCHORS RUNNING EAST-WEST WITH TIDE STREAM.

NOTE: FISHED OVERNIGHT.

Table 24

DATE 9th – 10th / 9 / 80 SITE STEAMER POINT, HIGHCLIFFE, CHRISTCHURCH BAY. DORSET. DEPTH 6·5m.

TIME SET 15-00 TIME HAULED 11-00 TIME FISHED 20 hr.

SECCHI DISC DEPTH 1) 1·8 m. 2) 1·8 m. AV. 1·8 m.

% TRANSMITANCE AT NET DEPTH 1) ____ 2) ____ AV. ____

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
MACKEREL	14	10	3	14	10	8	9	10	78
HORSE MACKEREL	7	7	4	6	3	6	6	7	~~46~~ 46
POLLOCK	1	2		2	2	3	2		12
POUT			2	2	6	1		1	12
GURNARD								1	1
BASS			1		1				2
SHAD		1		1			1		3
SMOOTH HOUND.						1			1
MULLET				1					1
HAKE								1	1
Total in each net	22	20	10	26	22	19	18	20	Total Catch = 157. fish

Sea State:- ~~Calm~~/Rough Average Surface Irradiance/hour fished ___ mW

Wind: SW 6-8 Sky:- ~~Overcast~~/Cloudy/~~Clear~~

Comments: NETS SURFACE RIGGED, SO THAT JUST OFF BOTTOM AT LOW WATER. BOTTOM IS SAND/CLAY COVERED WITH SEA LETTUCE (ULVA LACTUCA) WHICH DRIFTS WITH THE TIDE.

NOTE: FISHED DAY AND NIGHT; FROM CONDITION OF MACKEREL IT SUGGESTED THAT THEY BEEN CAUGHT EARLY IN THE PERIOD FISHED.

Table 25

DATE 10th – 11th / 9 / 80 SITE STEAMER POINT, CHRISTCHURCH BAY. DEPTH 6·0 m

TIME SET 17-30 TIME HAULED 07-30 TIME FISHED 14 hr

SECCHI DISC DEPTH 1) 1·75 m. 2) 1·7 m. AV. 1·725 m.

% TRANSMITANCE AT NET DEPTH 1) ____ 2) ____ AV. ____

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
MACKEREL	1	1			1		1	1	5
HORSE MACKEREL	1	4	2	2	4	2	4		19
POLLOCK	1	2	1		1		1	3	9
POUT			1	1	1	1		1	5
BASS				1		1			2
SHAD					2		1	2	5
DOVER SOLE		1							1
Total in each net	3	8	4	4	9	4	7	7	Total Catch = 46 fish

Sea State:- ~~Calm~~/Rough Average Surface Irradiance/hour fished ___mW

Wind: W-SW→NW 8→5 Sky:- Overcast/~~Cloudy/Clear~~

Comments: THE WATER WAS VERY COLOURED FROM SILT STIRRED UP BY GALE. THE 2 END NETS; GREY AND BROWN WERE FULL OF WEED AND HAD DRAGGED SO THAT THE BROWN NET LAY ACROSS TIDE. NETS SURFACE RIGGED. NOTE. FISHED OVER NIGHT.

Table 26

DATE 30th/9 – 1st/10/80 SITE STEAMER POINT, CHRISTCHURCH BAY. DEPTH 6·5 m.

TIME SET 11·30 TIME HAULED 0900 TIME FISHED 21 hr 30 min.

SECCHI DISC DEPTH 1) 1·25 m. 2) ____ AV. 1·25 m.

% TRANSMITANCE AT NET DEPTH 1) ____ 2) ____ AV. ____

Species \ Net Colour	Grey	Brown	Red	White	Yellow	Black	Green	Blue	Total of each species
BASS			2						2
MULLET						1			1
POLLOCK.				1					1
Total in each net	0	0	2	1	0	1	0	0	Total Catch = 4 fish

Sea State:- ~~Calm~~/Rough Average Surface Irradiance/hour fished ___mW

Wind: SW 6-7 Sky:- Overcast/~~Cloudy/Clear~~

Comments: NETS; SURFACE RIGGED. ALL NETS FULL OF WEED. WATER VERY TURBID FOLLOWING STORMS. MOST OF THE MACKEREL / HORSE MACKEREL HAVE MIGRATED WEST.

NOTE: FISHED DAY AND NIGHT.

Table 27

Depth: Surface set

Water: Very turbid (Secchi disc depth 2.75, 1.8, 1.7, 1.25m)

	Brown	Black	Grey	Red	Green	Yellow	Blue	White	Total
	1	1	0	1	1	(1)	3	2	9 +1
	20	19	22	10	18	22	20	26	157
	8	4	3	4	7	9	7	4	46
	0	1	0	2	0	0	0	1	4
Total catch	29	25	25	17	26	32	30	33	217
Proportion of catch	0.134	0.115	0.115	0.078	0.120	0.147	0.138	0.152	
1- prop. of catch	0.866	0.885	0.885	0.922	0.880	0.853	0.862	0.848	

The bracketed yellow value has been obtained from the mean proportion of fish in the yellow net in the 3 later cases, i.e. 11.0% of the total catch.

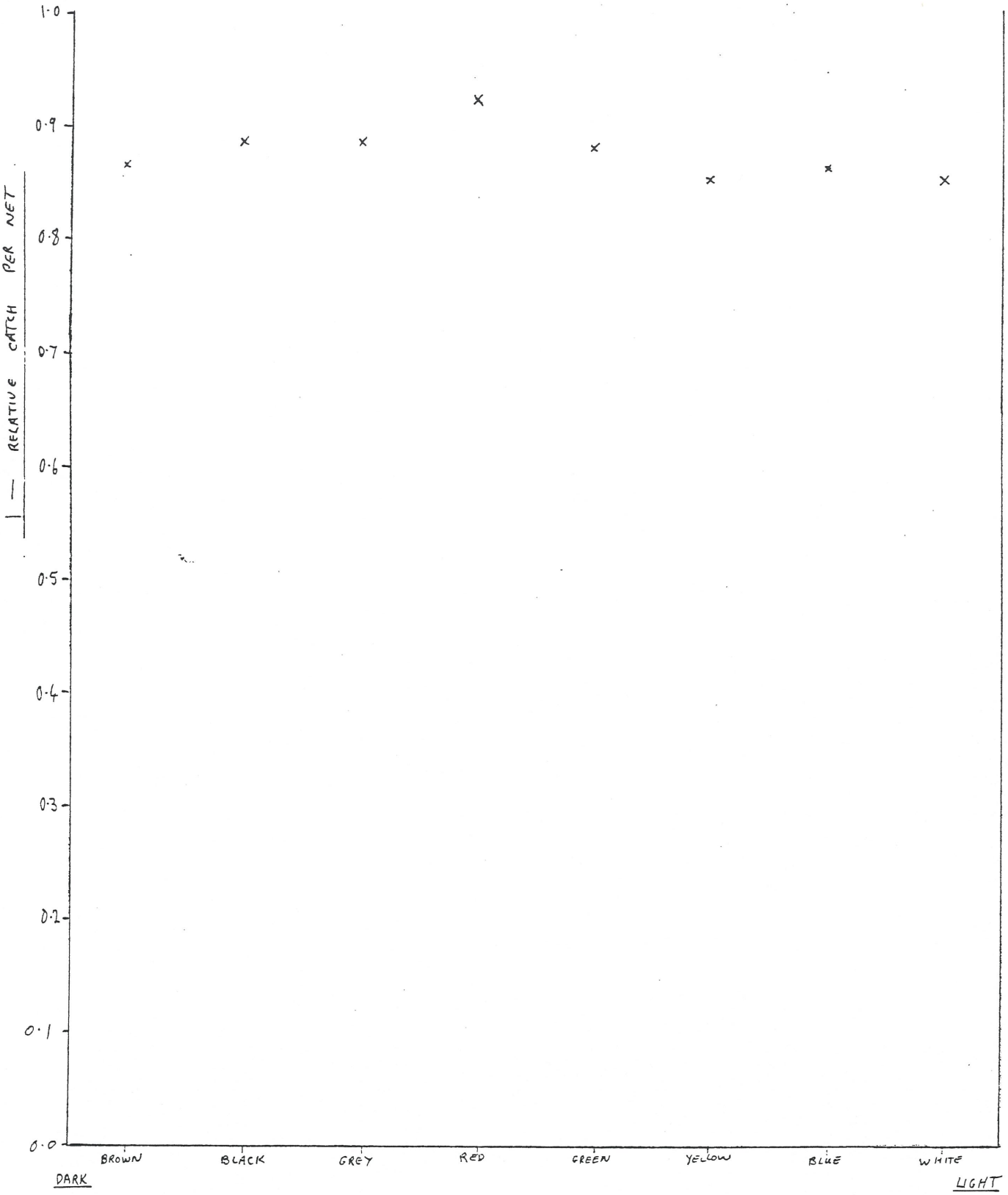


fig 36: RESULTS FROM SURFACE FISHING IN CHRISTCHURCH BAY AREA (SECCHI DISC DEPTHS = 2·75, 1·8, 1·7 AND 1·25 m) ON 8-9/9, 9-10/9, 10-11/9 AND 30-1/10/80

Nº OF TIMES FISHED = 4 ; TOTAL Nº OF FISH CAUGHT = 216. (INCLUDING 1 SMOOTH HOUND.

Discussion

Comparative fishing as a research tool which at first looks ideal, due to the apparent simplicity of a gill net design, but with actual use and experience one gets a feel for the intricacies of its design and their major effects upon the catching efficiency. One of these factors affecting efficiency is that the fish become aware of the net's presence due to visual stimuli. This may result from visible frame lines, floats, knots, twine thickness or slackness of hanging of the net; as well as the aspect which I have been studying, i.e. colour. Conversely, the presence of seams and discontinuities are reported to actually enhance capture.

The limitations of fishes' vision are not fully understood; it is thought that they can see up to 1-4 metres in clear water (Fridman, 1969) but their actual perception is even less well understood and thought to vary between species. Throughout my project I have tried to use two other techniques to ascertain visibility apart from the inference of catch figures; these are (i) diver observations, and (ii) photographic representations. Divers' vision, like that of fish, is not fully understood; it is difficult to quantify and visual perception changes between individuals. Also it is not known how comparable man's visual perception is with that of fish. Photographic observations appear to give the same trends as diver observations in the shallower depths, e.g. 14m with one notable exception, RED, which appears lighter.

During my experiments I have tried to record as many factors effecting the ambient light levels as possible; sea state weather, wind direction and strength, water depth, Secchi disc depth, beam transmittance, times of day fished and when known, the type of sea bed. Much of this data has had little use in my analysis, largely due to a lack of results. Apart from influencing the actual light levels at any depth, some of these factors also affect the degree of polarization of the light. This

is thought to be an important factor in fish that can detect it visually for shoaling and behavioural purposes. Polarization of the light is least when the sky is overcast and at dusk and dawn. The latter two periods are the traditional times to fish with gill nets, especially for pelagic species, e.g. sardines, as the nets become less visible with reduced polarization of the available light. The other main time for using nets commercially is at night, this being due to the reduced visible ranges in the lower light levels.

Previous work in the use of coloured nets or differing shades has been done either by comparative fishing which requires considerable time to get sufficient results for each standard condition, by diver observations or by photographic techniques (often with remote viewing in the case of T.V. cameras).

To my knowledge no-one has run comparative tests between these techniques in water of a constant type. From my observations it appears that the 3 techniques do all show the same general trends (except that the colour red appears lighter in photographs than it does by in situ diver observation but I have no way of quantifying the relationships. A further problem I have encountered is the dulling and slight discolouration of the nets that occurs through use (see page 20).

Water conditions defined have been the average between time of setting and retrieval. Thus with changing light levels, depth and water clarity during a tide cycle, it means that visual ranges will be constantly changing. But as depth changes substrate colour and water type do not change much over the periods fished, we can ignore the small changes in their absolute values and just note the optimum colour and the relative performance of each net. But on the day to day time scale the water type may well change sufficiently so as to affect the actual order of net visibility.

Hemmings and Lythgoe (1965) stated from their diver observations that "the optimum net brightness required to match the water background is comparable both by day and night although nets may need to be somewhat brighter at night for perfect camouflage than by day". The daytime visual ranges they recorded were about 10 times those observed at night. Although I conducted similar observations of my nets in daylight, I did not conduct any night dives as it would require small frames of netting, as diving on actual nets would be too dangerous at night.

My daytime diving results showed similar trends to those of Hemmings and Lythgoe, although I used some different colour nets to them and my observations were in a different water type and sea area (This was done in the Mediterranean, off Malta, and in the Moray Firth, Scotland).

Following their observed similarity in the optimum colour/brightness for both day and night, I have combined the catch figures for daytime fishing, nighttime fishing and those from when the nets were fished 24 hours at a time (these being the most common due to the logistical problems of making 2 trips a day to set and haul the nets). These results have also been divided into 'fishing shallow', i.e. ≈14m and 'fishing deep', i.e. ≈30m. The shallow water results were then subdivided according to water type (Secchi disc measurements < 3.5m, 3.5m - 5.5m, and > 5.5m). The few additional catch results from surface rigged nets in Christchurch Bay are all for turbid water. This still leaves very few catch statistics and as a result the sub-analysis, species by species, is not possible at present.

In the interpretation of the results, correlation coefficients were largely inconclusive due to the few catch results available to compare with diver observations in each water type. By comparing catches in each net in each water type, interesting results can be obtained. Normally the white net would be used as standard catch (100%) against which the others can be compared. But as in 2 of the 5 water types the

white made no catches, an alternative colour must be used as a standard with its catch = 100%. For this I am using the green catch figures as green nets are commercially available and caught in each water type, although brown, grey, red or blue catches could equally well be used as standard.

Plymouth Sound area; depth ≈ 14m, Secchi disc depth <3.5m

Due to the high turbidity of the water the diver observed ranges were all low and with little range between them. The least visible colours being the brighter ones, i.e. white, blue and green (see Figures 22 and 31). From fish catches taking green as = 100% then red and blue = 300%, brown and yellow = 200%, grey and black both also 100% and white = 0. Though red and blue nets are showing a 3 fold increase in catch over the green this is of little significance as 12 of the 13 fish upon which it was based were caught upon one occasion (see Table 6). This may also explain why the white net did not catch on either occasion and there is limited relationship between catches and colours of least observed visibility (see Figure 24).

Plymouth Sound area; depth ≈ 14m, Secchi disc depth 3.5m - 5.5m

With the improved water clarity sighting ranges have increased slightly and the range of observed ranges has increased. The least visible colours are now yellow, blue and green, i.e. a shift away from the light colours (see Figures 25 and 31). Taking the green catch as 100% then blue caught 75%, grey 50%, brown and red both 25%, whilst yellow, black and white did not catch. This is based upon 2 sets of catches in which blue, green and grey caught consistently. Yellow though least visible to the divers never caught, and conversely, grey which was second from being the most visible, caught quite well (half as much as the green net's catch)(see Table 11).

Plymouth Sound area; depth ≈14m, Secchi disc depth >5.5m

With this relatively clear water all visual ranges were increased although the range of them remained similar to before (see Figures 28 and 31). The least visible colours showed a further shift towards being darker with the least visible colours being green, grey, yellow and blue.

From fish catches (see Table 18), taking green as 100% then blue = 312.5%, grey = 287.5%, yellow = 162%, red, black and white = 125% and brown = 87.5% (Taking undyed (white) as 100% then blue = 250%, grey = 230%, yellow = 130%, red and black 100%, green = 80% and brown = 70%).

In clear water, with the exception of green, the least visible nets were among the top catchers, (see Fig. 30), with blue catching $2\frac{1}{2}$ times as much as an undyed net; that is 3.125 times as much as for the green net.

In fishing at depths of around 14m in the 3 water types, dyeing the nets improved their catches except for green and brown in clear water and black and yellow in the intermediate water type, these showing either a reduction in catch or no improvement over the white net. The blue net caught well in all cases, being top net in both high and low visibility water and second to green in the intermediate.

Plymouth Sound area; depth 30m, clear water

When diver observations were made the water was relatively clear but was carrying patches of plankton which covered the nets, possibly masking their colour to some extent. The visual range of each net were as high as for the 14m depth observation, but the range of the ranges measured was quite small with the exceptions of black and yellow, which were much more visible than the other colours. The least visible colours were blue, then white/green and grey (see Figures 32 and 33).

From catches, taking green as 100%, then black and yellow also = 100%, grey and red = 92.5%, blue = 61.5%, white and brown = 23%. (Taking

undyed (white) as 100% then black, green and yellow = 433%, grey and red = 400%, blue = 267% and brown = 100%).

Therefore dyeing nets any of the colours but brown should at least double the catch in this situation (see Table 22).

The catch results contain a high incidence of dogfish (elasmobranchs), so excluding elasmobranchs as they have only scotopic (non-colour) vision then taking the green net's catch as = 100%, it gives yellow = 157%, grey = 143%, blue = 100%, red = 57%, brown and black = 29% and white nets made no catch of teleost fish.

One interesting result from this is that the black net was equal top net for fish overall, but most of these were dogfish. Considering only the teleost content of the catch it puts black equal second from bottom with brown. This high incidence of elasmobranchs in black nets is an interesting result as ray nets are traditionally black. The top catching net overall and for teleosts only is yellow with grey second; this is also surprising as yellow, like black, was given significantly higher visual ranges than for the other colours. This is possibly the result of a shortcoming of using divers for observations inasmuch as the human brain and eye does not always let you see what you should see, e.g. reds are perceivable at this depth, although due to selective adsorption red wavelengths are almost absent from the available light, thus the "red" object would actually not be reflecting very much light and should thus appear virtually black.

Christchurch Bay, surface rigged, Secchi disc depth <2.75m

The water here was always turbid and full of silt; due to this I would expect light coloured nets, i.e. white, blue and yellow to have least contrast and therefore the lowest visual ranges and the highest catches, but as the range of visual ranges would be expected to be small in this type of turbid water it would reduce the difference in catches between the nets (see Table 27).

Taking the catch of the green net as 100%, then white = 127%, yellow = 123%, blue = 115.5%, brown = 111.5%, black and grey = 96% and red = 65.5%.
(Taking white as 100%, yellow = 97%, blue = 91%, brown = 88%, green = 79%, black and grey = 76% and red = 51%).

Therefore in this very turbid surface waters the diver observations made in Plymouth area would suggest the type of trend observed with the lightest colours catching most. The top catching colour on average was white, which probably best matches the brightness of the background for minimal contrast and dyeing nets only tends to reduce their efficiency. Much of the fish in these experiments with surface rigged nets was mackerel (41% of total fish) and 31% were horse mackerel (scad), this is in contrast with results from Plymouth where pollock constituted 40% and wrasse species 29% of all fish caught, much of the remainder being dogfish.

From diver observations in the Plymouth area the colour expected to have least contrast, i.e. the colour that best matches the water background brightness, changes with depth and water clarity, e.g. Secchi disc depth.

In the most turbid waters the best colour was white as this was the lightest colour amongst the nets. As the water becomes clearer then the optimum becomes darker, through the colours blue, yellow, green, grey, black and brown (see Figure 31). From photographs (Plates 3-10) red appears to have a brightness intermediate between green and grey although diver observations and fish catches appear to suggest a darkness nearer to black or brown. With the water types in which diver observations were made at about 14m depth in the Plymouth Sound area the darkest colour observed as being the best match of the background was green, with grey and yellow being slightly darker and lighter respectively according to visual ranges observed on that occasion. Top colours from catches were blue, grey and yellow, this showing some similarity

with diver observation.

Overall the results from the 8 colours of nets both by catch and diver observations suggest that it is brightness of colour rather than the actual colour that is the over-riding factor in the visibility. This supports all other work done in the field. In the diving observations it was noticeable that there was a difference between the brightness and colour contrast, especially with the yellow net in Cawsand Bay. In close proximity to the net it looked yellow and bright but as you move away the strong colour was rapidly lost leaving only a difference in brightness which soon lost its contrast and totally merged into the background. (It should be noted that in all my experiments the nets were fished mainly over silt or sand; these being light coloured bottoms). Other researchers, notably Molin with his trial fishing in Swedish lakes and on the east coast, states that the brightness of the substrate is an important or even the controlling factor in the choice of the optimum net colour/shade. The optimum in some cases varies from species to species although I have insufficient catch data to test for this in any one situation.

One way to attain a near optimum net in all water types is to go away from trying to match the background and go for a transparent material, i.e. monofilament, but monofilament though shown to catch better in daytime than conventional twine nets due to near invisibility, does tend to be extremely bulky due to inherent filament stiffness. This is also important in that due to its stiffness it does not have good fish retention properties and a lot of fish once dead and not struggling tend to fall out of the netting and are lost (observation on a parallel project into "Ghost Fishing" by Mike Smith). An answer to the stiffness problem of monofilament is to use a finer filament but this loses physical strength. An alternative is to use very fine filaments twisted together to form a "transparent" twine. This is known as "multi-mono", and though a softer twine it does have a higher visibility than monofilament.

Summary of catches

It is widely believed that coloured nets fish better than white (undyed) nets; this is reflected in the fact that the main netting retailers, especially Bridport Gundry, stock mainly blue and green nets among other colours and white nets are becoming increasingly difficult to obtain. This trend is in some ways a return to the days when, before the introduction of synthetics, natural fibre nets were all coloured as a consequence of the preservation treatment applied. The nature of this varied from one area to another according to tradition, availability and which was found to catch best.

In my experiment I have used 8 nets, white (undyed), brown, black, grey, red, green, yellow and blue. Fishing has been carried out in 2 main areas, primarily in the Plymouth Sound area at depths of around 14m and a couple at about 30m. The other results were for surface rigged nets in Christchurch Bay, Dorset.

The following is a breakdown for each colour in turn of its suitability in each situation tried.

White: In the lowest visibility water in Plymouth Sound at 14m, the white net was useless, catching nothing; similarly in the intermediate water type (see Tables 6 and 11). Only in the clearest water did it make any catches at the 14m depth, here catches were comparable with black and red and slightly better than brown and green overall (see Table 18). On individual occasions the white net never caught more than half as much as the top net which changed from occasion to occasion, suggesting either substrate influence, randomness of catches or species differences.

At 30m depth the white net was equal bottom with brown although, unlike all the other nets, the white only caught dogfish (see Table 22).

In contrast to the Plymouth results for white, when fished as a surface

net in the turbid waters of Christchurch Bay the white net was top overall and top or amongst the top nets on each occasion. In this situation the results suggest a definite disadvantage to having coloured nets (see Table 27).

Brown: Before the introduction of synthetics nets were commonly cutched for preservation; this gave a brownish colouration. At 14m in the Plymouth Sound area the brown net catches were average to poor, especially in the clearer water types (see Tables 6, 11 and 18). At 30m the brown came equal bottom with white; although the catch in the brown consisted of more teleost and less elasmobranch fish than white (see Table 22).

When surface rigged in Christchurch Bay the brown catch was variable; on some occasions near bottom and on others amongst the top catching nets (see Table 23). Overall it was second only to yellow and white.

Black: At 14m black catches were low in the lowest visibility water type, zero in the intermediate and improved to give an average catch for the clearest water where the least visible net tends towards a darker colour (see Tables 6, 11 and 18).

At 30m black was one of the top nets with nearly all of its catch being elasmobranchs unlike green and yellow which also caught as much but with a much smaller proportion of elasmobranchs in the catch (see Table 22).

When surface rigged in Christchurch Bay the black net caught consistently but not very well (see Table 27).

Grey: The grey net at 14m caught consistently and in the clearer water did best with catches second only to blue and on several of the periods fishing the grey caught almost double that of other colours. In the more turbid waters it did less well (see Tables 6, 11 and 18).

At 30m the grey and yellow were amongst the top catching nets with the bulk of the catch being teleost rather than elasmobranchs (see Table 22).

Surface rigged in Christchurch Bay the grey net catches were only average to poor, with zero catches on half the occasions (see Table 22).

Red: In turbid water where a light colour would be expected to be best the red net came top with blue for catches (see Table 6). For the less turbid and clear water types the red net did less well with some of the lowest catches during each trial (see Tables 11 and 18).

At 30m red did fairly well with catches comparable with the other top colours in this situation, namely black, grey, green and yellow (see Table 22).

Surface rigged in Christchurch Bay the red net in total caught least and this was so on all but one occasion when it was top net (see Table 27).

Green: At 14m the green net caught most in the intermediate water type (see Table 11) and was amongst the bottom colours in the turbid and clear cases (see Tables 6 and 18).

At 30m the green net caught well (see Table 22).

Surface rigged in Christchurch Bay the catches were consistently above average (see Table 27).

Yellow: At 14m in turbid waters the yellow net caught consistently well (see Table 6). In intermediate water (least diver observed range) the yellow net, together with the black and white never caught at all (see Table 11). In the clearest water type the yellow net catches ranged from top net to near bottom with an average total catch for the water conditions. (see Table 18).
At 30m the yellow net did well with the top catches of teleost fish on each occasion (see Table 22).

When surface rigged the yellow net did consistently well and the total catch was second only to the uncoloured net (see Table 27).

Blue: At 14m this colour did consistently well coming top or near top in each of the 3 water types specified (see Tables 6, 11 and 18).

At 30m the blue net was not very exceptional although it did catch very few elasmobranchs, i.e. its main catch was teleost fish (see Table 22).

When surface rigged in Christchurch Bay this net caught fairly consistently and its total catch placed it second only to the yellow and white nets (see Table 27).

In conclusion, the limited catch data restricts any conclusions to only a small degree of certainty. In each situation the optimum colour appears to change, although some colours, e.g. grey, blue and yellow, appear to do quite well in all situations. Others appear to work only in some situations, e.g. for surface rigged nets in Christchurch Bay white (undyed) nets overall did better than dyed nets with the exception of blue or yellow on different occasions. In comparison in the Plymouth Sound area at 14m with a similar water type the top nets were blue and red, with white now the bottom net with zero catch on most occasions.

At 30m depth colour appears to have a less marked effect upon total catch in each colour; with the exception of brown, white and to a lesser extent, blue.

Diver observations tend to show a limited correlation to the catches in each situation in the Plymouth area (see Figures 24, 27 and 30), but the results from surface rigged nets in Christchurch Bay do show excellent correlation with diver observation for similar conditions in the Plymouth Sound area. This might be just a coincidence as the diver observations were at 14m depth not for surface waters. The lack of correlation for the Plymouth area may be improved upon by more results, limiting the range of Secchi disc readings covered by each water type classification and fishing only one area or type of substrate. The optimum colour for each species is difficult to determine due to the lack of results to date; but with any future work prospects are much

brighter now that the initial teething problems have largely been overcome.

Recommendations for further work

I feel that this project deserves continuation to collect more data so that a more meaningful analysis of the results can be made.

Anyone taking up this recommendation should be aware of the logistical problems in setting up this type of experiment and should aim to get the bulk of it concluded during the summer and autumn terms as equipment is likely to be more available, weather conditions favourable and catch rates higher than in the winter and spring. This also leaves plenty of time to write up the report before Easter.

Problems likely to be encountered apart from those of logistics and operating from a vessel not designed for fishing purposes include designation of water type and net colour (the latter will discolour with use). Water type will change continually with each tide, day and season. The available light will also alter with water type, depth, substrate, orientation of viewing, sea state, time of day, altitude of the luminary (sun or moon), cloud cover and polarization.

To designate the water's attenuation criteria on each occasion a simple but effective method is required. Previously I have used a 30cm diameter "white" Secchi disc, this is of only limited value as any sighting lengths measured are for the surface water and are prone to many variables and unknowns including decolouration of the disc with use, its reflectance (ρ), the proportion of light upwelled and surface reflections from the waves. Furthermore the water type is defined in terms of the combined coefficients c and k. To define each, a second instrument (e.g. a Transitometer) is required to be used simultaneously to determine k.

By this method a lot of apparatus is required, and such problems as equipment failure, unavailability or loss are likely to be encountered again.

A better alternative would be to use a "black" Secchi disc, observed through a face mask or glass bottomed bucket; this would give a vertical black body distance. Reflectance would be zero and contrast = -1. Then $£_c$ and $£_k$, (1/c and 1/k) can be estimated directly (see page 41).

Another problem I encountered was that no measure of the light reaching the sea surface during fishing was available as the Actinograph was out of calibration and not working.

If, in future, accurate designation of the water type and sufficient catch data is obtained, then an optimum net colour/shade for any particular species, depth, sea area or overall conditions should be determinable either by graphical means or by formulae from a few water type measurements; see Fridman (1969) and Tsuda and Inoue (1973).

A further improvement could be made by being species specific in the analysis, i.e. pollock or mackerel as these have been the most prolifically caught species to date in my experiments and it is widely accepted that there are slight interspecific variations in fish vision. Dr. M.B.A. Djamgoz, Imperial College, London, has been doing research into field of fish vision.

An alternative approach to mine, which is probably better, would be to firstly use a series of grey nets of differing shades, from white through to black, as they reflect light indiscriminately. Then, from either catch data and/or diver observations determine an optimum shade. This method is based upon the widely accepted fact that although an optimum colour can have a several fold effect upon catches, the overlying influence is the shade (brightness) of colour. If this aspect was to be taken up in a further project then it might be worthwhile contacting I.C.I. Ltd., Dyes Division, who in the past have supplied nets of various shades of blue and grey - see Hemmings and Lythgoe (1965).

Having obtained an optimum shade for minimum visibility in a certain water type, then using nets of different colours, but constant shade of colour, it might be possible to obtain a further slight reduction of visibility from the colour contrast reduction. Assuming that minimum brightness and colour contrast was obtained for the prevailing conditions, then uniformly dyed nets would still not obtain absolute zero contrast due to the distribution of light underwater. The ideal net twine would be dark on top, white beneath and intermediate shades in between so that it matched the water background from whatever direction observed (It should be noted that this is the normal method of camouflage used by fish).

Hemmings & Lythgoe (1965) from their diver observations on blue nets of varying brightness, concluded that the brightness of net best matching the background is comparable both by night and day, although at night the optimum was slightly brighter. This statement has formed the basis of the analysis of my results, where day and night and both day and night catches have been combined for each water type specified. Do fish catches support the above hypothesis?

A final innovation worth exploring is the use of "rainbow" coloured nets. These have been used in Scandinavia but are apparently no longer available and no literature has ever been published upon them to my knowledge. Construction could either be from patches of coloured netting, tie-and-dye type dyeing of netting or dyeing the twine varying shades/colours and Bridport Gundry would manufacture the sheet netting as a special order to your specifications, i.e. mesh size, double knotted, etc. Catches from a "rainbow" type net are likely to be consistently better than any one colour or brightness net. Larkins (1963 and 1964) describes how a mixed fleet of salmon gill nets; some mono and some multifilament catches more than fleets of either one or the other.

In all forms of research into fish catching methods a better understanding of the constraints of fish vision and perception is required together with a knowledge of how fish behave in the vicinity of fishing gear. Also we need to extend our understanding of the propagation of light underwater, its polarization and variation with sea state, weather, time and season.

An offshoot of this type of research could be that providing the nature of the water type could be indicated in a simple manner such as by a Secchi disc reading, sea bed type, colours and the depth to be fished was given, then from a chart the appropriate shade of grey, for example, could be read off. Then the required dye could be applied to the sheet netting prior to construction of the net, to give a more efficient net. With this type of "Off-the-shelf" D.I.Y. dye kit it means that commercial fishermen can without any difficulty and at minimal cost of time or money, apply science to enhance their skills. Fishing net stockists would no longer need to keep stocks of various colours and shades of netting to satisfy demands. Only a few different colour dyes that can be diluted to requirements need be stocked.

Apart from sales to commercial fishermen a sizeable demand is also likely from part-time fishermen and others, partially for its novelty appeal.

Provided research carried out at Plymouth Polytechnic can approach the stage where the net colour/shade requirements of any water type could be easily determined, then it would be worth running consumer tests and a financial appraisal of this scheme.

Finally, any knowledge gained from this type of study into the attainment of an invisible gill net can be used in reverse in the design of "leaders" for trap nets. Here the intention is for the fish to see the net and follow along it without becoming entangled in it by trying to pass through or frightened away if the colour is too bright.

APPENDIX

A1 Designation of twines and netting

Twine is usually made of 3 strands, each being made up of the same number of yarns. The strands are usually laid up with the opposite direction of twist to the final twine. The final twine is usually right hand lay this usually designated as "Z" lay as opposed to left hand lay, which is designated as "S" lay.

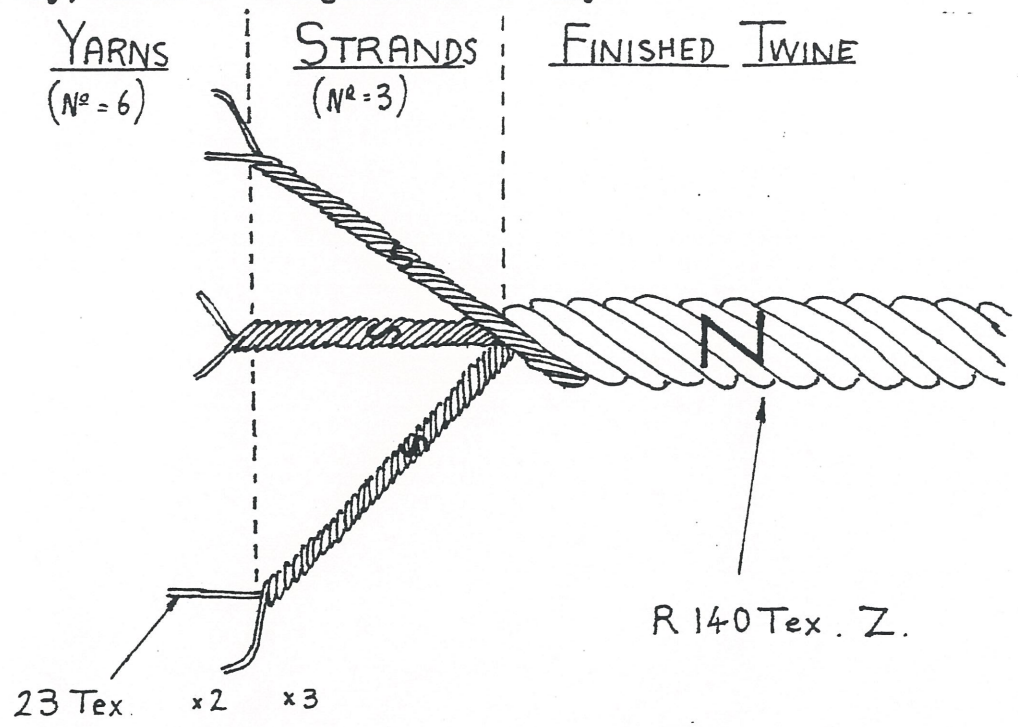


Figure 37 An Example of the complete designation of netting twine.

The finished twine is designated by its weight per unit length. The units of this are various; the most commonly used by British net manufacturers being a denior count (g/9 Km of yarn), e.g. 210d/6 means each yarn weighs 210 gram per 9 Km and there are 6 yarns; 3 strands of each with 2 yarns. (see Fig. 37)

This latter is abbreviated by Bridport Gundry to 2Z meaning that the twine has 2 yarns per strand and the finished twine is Z laid (right hand). To unify the various forms of twine designation the "Tex and R. Tex" system is being adopted.

Weight of a single yarn (g/Km) = Tex value

So, Tex (g/Km) = $\frac{\text{denier}}{9}$ (g/9Km)

$\therefore$ 210 d/6 = $\frac{210}{9}$ x 6 yarns

= 23.3 Tex x 6 yarns = 23.3 Tex x 3 strands x 2 yarns

The R. Tex value is the weight of the finished twine

R. Tex $\tilde{\sim}$ Tex x no. of yarns

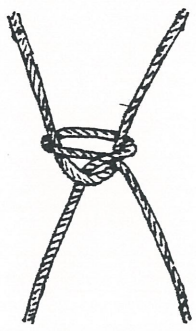
e.g. 23.3 Tex x 6 yarns $\tilde{\sim}$ R140 Tex. Z

The actual value is slightly higher due to the loss of twine length in twisting the strands together (about 10% increase).

Rope can be designated in a similar way to twine but it is more common to refer to its overall diameter (Ø) in millimetres and indicate the material, e.g. nylon (Polyamide). Finished netting is referred to by the twine with which it is constructed, the mesh length between knots (= 2 bar lengths), the depth in meshes, stretched length (or number of meshes) and the type of knots used (whether single or double sheet bends (weaver knots), e.g. 210d/6(2Z), 3" mesh, 50 meshes deep x 100 yards, single knotted or R140 Tex Z, 75 mm mesh, 50 meshes deep x 100 metre, single knotted.

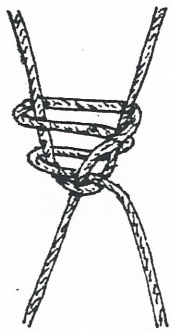
The sheet bend is the most commonly used knot by western net manufacturers. This takes two forms, either single or double. (see fig.38,39) The latter has better stability but is more expensive due to the additional twine used. Both knots are usually heat set at manufacture to improve their stability when transversely loaded.

Fig. 38



Single sheet bend

Fig. 39



Double sheet bend

The most commonly used twine today for gill/tangle nets in the U.K. is nylon; though polypropylene, polyester or polythene can be used. These have the advantage over natural fibres that they do not rot and therefore do not require preservation treatment. Furthermore, nylon has high physical strength and extensibility, this allows thinner twines to be used. The amount of twist of the twine also affects the extensibility; this being greater with a hard lay (more twists per metre). The direction of lay, S or Z does not affect the physical properties of twine provided there is uniformity in the lay. But when the twine is wetted it absorbs water and tends to swell slightly, this causes a slight stiffening of the twine and reduction of mesh size though with this size twine the loss of mesh opening is minimal. A further effect that results from this is a slight unlaying of the twine; this also occurs when the twine is under load. The significance of this in netting is slight but in the framing rope this will cause the mounted netting to roll around the rope as the rope unlays when under strain.

Greenofil rope is a combination of polypropylene and polyamide (nylon), this is so designed as to not twist when swelled by water, but will still twist when underload. Alternatively if 2 ropes differing only in the direction of lay (S and Z) are laid alongside each other then any torques that may result will be cancelled out and no overall twist will result when under strain.

A further option is to use braided ropes but these have the problem of mounting the net on them without slippage occurring in use. Similarly twines may be braided and netting constructed either knotted or knotless.

A2 Preservation and treatment of nets

Originally netting twines were of natural fibres, cotton, manilla, hemp, silk, flax, sisal, abaca, jute & coir and needed treating with some form of preservation agent to improve its properties, e.g. to prevent rotting. The type of treatment and how regularly it must be applied depended largely upon availability, economics and tradition, e.g. Indian fishermen in British Columbia, Canada, when fishing for salmon with drift nets dip their nets in copper oleate solution to get them progressively deeper blue as their fishing effort moves along the coast with the migratory fish. *(W. Stewart, personal communication)

With the introduction of synthetics, rotting by bacterial action has largely been eliminated and nets can now have continual usage with minimal treatment being essential. Although some is still carried out largely to satisfy personal requirements.

Preservation

Natural fibres

The principle reason for treatment is to prevent putrifaction largely by bacterial action, an excellent account of preservation used in Japan is given by Takayama & Shimozaki (1957).

1. Probably the simplest form is sunlight disinfection; in which bacteria and microorganisms are killed by drying the nets in the sun after use; usually daily. Often this is carried out in conjunction with other forms of treatment. In the Japanese anchovy purse seines the natural colour of cotton was preferred therefore the only additional treatment to sun drying was periodic boiling. Though it does not change the weight of a twine, the expected life is 1-2 years for cotton though only about a week if given no drying or sterilization. Now these have

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largely been superceded by white synthetic fibres which tend to be stronger and require little or no treatment.

2. Preservation by copper sulphate is used mainly on cotton nets for sardine, anchovy, mackerel and jack mackerel. The nets are dyed in a 0.1% solution which is at air temperature. This imparts a blue colour to the net. This in sea water gradually changes to copper chloride which is light greenish in colour but as it is less effective against microorganisms thus the net needs sterilizing in a 0.01% copper sulphate solution after each fishing operation. If the net is left exposed to air or sunlight the copper chloride that is formed in the sea from the copper sulphate would deteriorate the net. By this treatment it results in an 8% increase in net weight and expected life of the nets of 3-4 years for cotton. To store the net the copper compounds must be washed out in fresh water and the net then dried before storing in a cool, dark place.

3. Preservation by copper naphthenate is a comparatively recent treatment since 1951, this being largely due to its cost. The copper naphthenate is mixed with a sterilizing agent and diluted at normal temperature in kerosene. After soaking for 10-15 minutes the net is air dried. This gives a 12% increase in weight and redyeing is only required once a season, but nets treated in this way are prone to rodent damage when in storage.

4. Preservation by tannin (cutching) is probably the most common type of preservation used for natural fibre nets especially cotton. The tannin is derived from wattle or quebracho extracts. In Morocco for sardine nets tanning is with catechu or ground pine bark. This being further improved by using catechu and pine bark together or by coating with tar after dipping. (Levy, 1957)

Cutch (tannin) dyeing involves a series of boilings, cooling of the net in the solution then drying. Redyeing every 2 or 3 weeks is by a repeat process. This gives the net a brownish colour, 3-5% more weight and an expected life of 2-3 years provided that the net is dried once a week. The life span can be doubled if after tanning the net is soaked in 1% potassium or sodium bichromate. The redyeing is also extended to every 4 weeks with sun drying every 2 weeks. Other chemicals used with a tannin fixative include silicic acid and tartar emetic or potassium bichromate with copper sulphate and alum. Also catch (tannin) with testalin or carbolineum, or with copper vitriol and ammonium. (Von Brandt, 1957)

5. Coal-tar dyeing used on its own or with other preservatives is common. Dipping the cotton net in hot coal tar gives good preservation for 2 years with 3 monthly redipping but the net though having good abrasion resistance tends to be sticky and heavy (130% increase in weight). To remedy this the tar can be diluted with creosote which tends to cause the tar to deteriorate or with heavy oil which prevents the net drying up. Gasoline is a better solvent, but as with any thinning of the coal tar, preservative properties are reduced.
If tannin treated nets are tarred, redyeing with tar is required only every 5 months and expected life of the net is then extended to 4-6 years, but at the cost of the nets' weight being increased by 150%. Similarly for tarred copper naphthenated nets.

6. Acetylation or cyanoethylation of natural fibres, i.e. cotton, gives rot-proof twine by resin impregnation which requires special equipment. But once treated no retreatment is required and the net may be dyed or cutched for colour if required. This treatment of cotton gives 25% extra weight and 50-60 times the working life of untreated twine. But due to its introduction at about the same time as synthetics. It has not

been widely used since successful experiments with it in Scottish herring drift nets, salmon gill nets, in the late 1950's though it has found use in textiles. (Ruperti, 1957; Sandoz Ltd., 1957; Takayama & Shimazaki, 1957)

Other disadvantages of natural fibres when compared with synthetics are that they absorb water and swell thus causing the meshes to shrink, also become stiff and hard in water, have fairly poor abrasion resistance, high visibility, are prone to microorganism attack, low physical strength, low extensibility and elastic properties and high specific gravities. Synthetic twines have generally more favourable properties and have therefore superceded natural fibres in the world where synthetics are available. (Perlon-Warenzeichen, 1957)

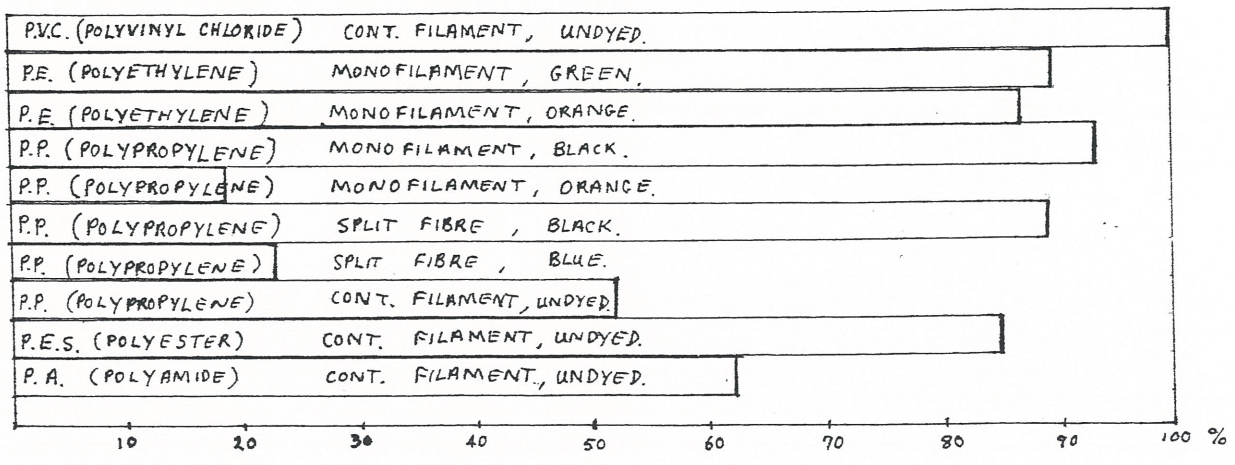
In fisheries where synthetic twines are required to sink quickly as with purse seines, their specific gravity is increased by tarring.

Due to the higher physical strength of synthetics the twine can be much thinner and therefore colour is less important in the visibility of the net. But thin twine tends to cut soft fish such as herring and due to the high extensibility of the twine fish become tightly gilled or tangled. So to improve this, a stiffener is applied, this is often tar or a bonding agent and heat setting. This also reduces knot slippage thus improving mesh stability and allowing such fish to be shaken out of the nets when hauling. (I.C.I. Ltd., 1957; Klust, 1957; Reuter, 1957). Synthetic twines; nylon and terylene were rapidly accepted in drift, gill and tangle nets for salmon, trout, sardines, herring, cod, borus, tilapia and other lake fisheries. (Amano, 1957; Du Pont de Nemours & Co. Inc., 1957; I.C.I. Ltd., 1957). The only problems found with synthetic twines is that nylon, terylene twines tend to be pristine white though this fades with use and also synthetics are found to deteriorate on the surface with long exposure to sunlight

though much more resilient than natural fibres. One remedy for protecting against sunlight deterioration is to dye with catechu or tannic acid and antimony potassium tartrate. (Klust, G., 1973; Perlon-Warenzeicherwerband, 1957) (see Fig. 40)

As synthetic twines are not very prone to rotting they do not need preservation treatment which tended to colour the netting as well as imparting other properties. But many fishermen still demand coloured nets; from reddish brown to green or blue or blue-grey (colours of traditional natural fibre dye/preservatives) as these they feel give the best catches. Dyeing synthetics is best done at manufacture, although tinting can be done with asphalt based solutions (I.C.I., Ltd., 1957). Synthetic dyes such as "Dylon", "Perliton", "Telon" or if green is required, green "Cuprinol" mixed with a fixative from Cuprinol Ltd. are available to dye synthetics almost any colour. (Burgess, 1980; Perlon-Warenzeicherwerband, 1957)

Though with the advent of translucent monofilament polyamides which have been shown to be more efficient than multifilaments dyed to reduce their visibility, which when introduced were considered a great advance from the highly visible natural fibres (Klust, 1957), now with synthetics especially monofilaments, daytime fishing with gill nets is being successfully practiced whereas once it was considered futile. (Von Brandt, 1972).



(after Klust, G., 1973, redrawn)
Figure 40. Remaining breaking strength of netting yarns as a percentage of initial breaking strength after exposure to 1500 sun hours.

A3 The validity of Photographic Evidence

The human eye can easily be compared to a camera; both have a lens to produce an image, an iris to control its brightness and can bring objects at all distances into focus on the sensitive surfaces, i.e. retina or photographic emulsion respectively.

In the eye the sensitive surface of the retina consists of rods and cones. The rods are for monochromatic "night" vision. The cones are for colour "daylight" vision; these take 3 forms; one sensitive to violet/ blue light, one to green, and one to orange/red. These pigments have fairly "normally" distributed peaks of sensitivity and these overlap so for example yellow light will stimulate a proportion of both green and red cones to give a "yellow" stimulation to the optical part of the brain.

Colour photography using KODAK Ektachrome 400 film works on a slightly different principle. Rather than pigments sensitive to the 3 primary colours:- blue, green and red as occurs in the eye. The photographic paper is "colour reversal type"; this means that it uses 3 complementary colour dyes:- Cyan, Magenta and Yellow (see Fig. 41).

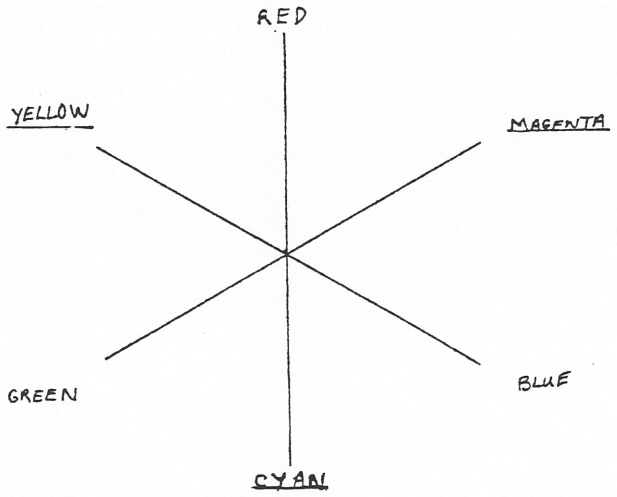


Fig. 41 Complementary colours

Cyan transmits blue and green whilst absorbing red, this is said to be complementary to red.

Magenta is similarly complementary to green and yellow is complementary to blue (see Fig. 42)

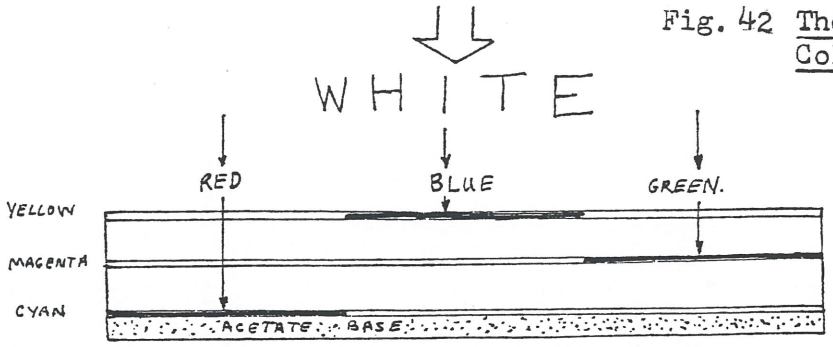


Fig. 42 The principle of a Colour Reversal Film

Thus the process is said to be subtractive. Obtaining the true colours occurs in complicated "reversal" processing of the film for slides or prints

In practice these idealised spectral characteristics of Cyan, Magenta and Yellow do not actually occur due to the transmission curves of the dyes from which they are derived. (see Fig. 43).

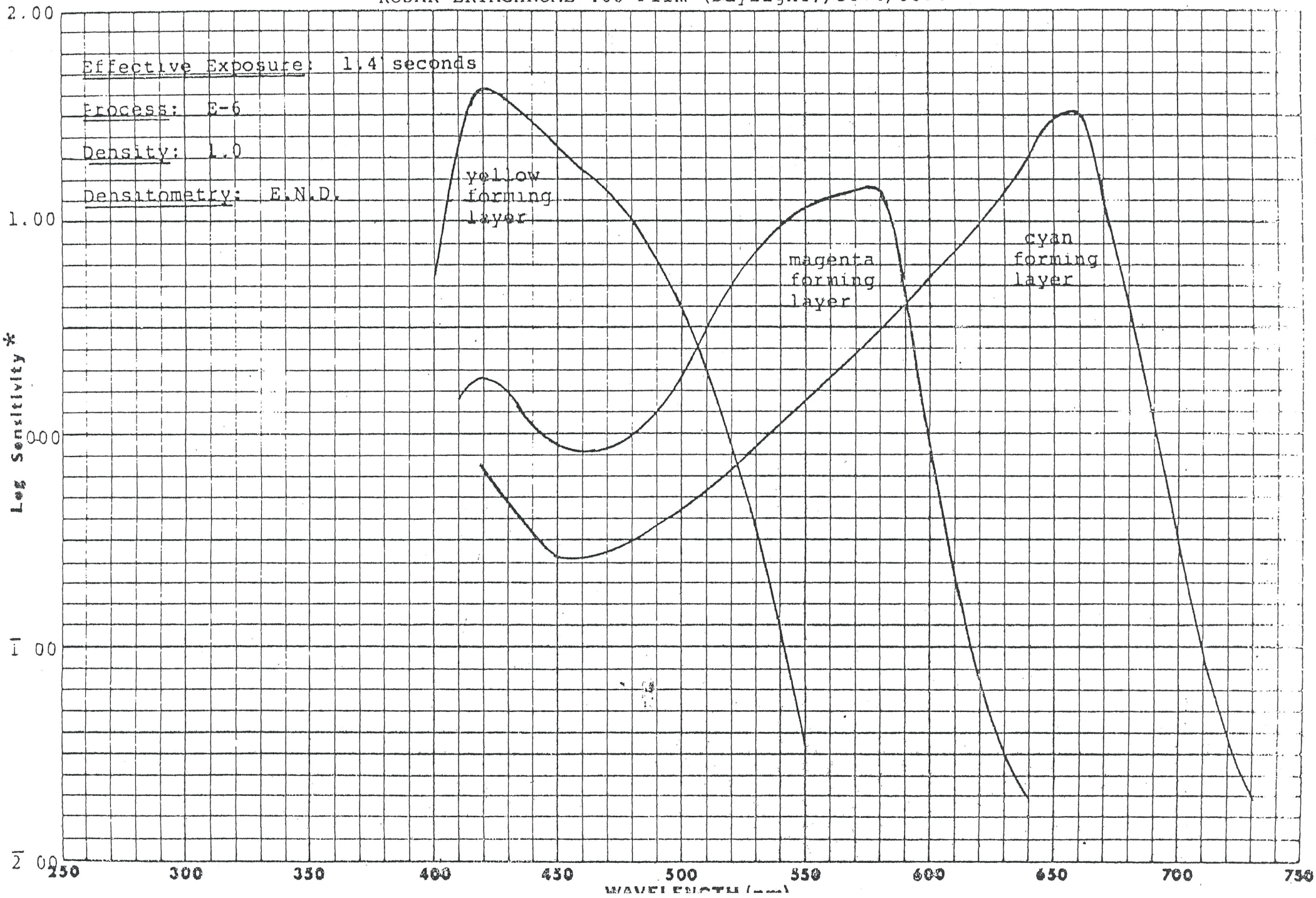
Cyan which should absorb all red whilst transmitting blue and green in fact absorbs some blue and green whilst transmitting some red.

Magenta does not absorb all green, also absorbs too much blue and some red; both of which it should transmit. Yellow transmits only slightly in the blue where it should absorb, it also absorbs slightly in the green.

These shortcomings of the dyes are compensated for in their mixing to give faithful "daylight" colour reproduction. Also with photographic material the degree of resolution is limited by grain size though this is not relevant to my work.

The Ektachrome 400 film used in this study is designated as a "Daylight" film. This means that the colour material has been balanced for natural daylight colour temperatures. So if exposed to artificial light it will give "warm" (reddish) colours. Similarly fluorescent lighting will give a "greenish" hue to a subject.

KODAK EKTACHROME 400 Film (Daylight)/5074/6074



In these cases the film is giving a true representation of the situation, but man does not think he sees this as the brain compensates.

Similarly when diving the human brain makes you see colours; near what they would appear in "daylight", e.g. a gurnard appears red. In reality the light coming from the subject is largely monochromatic (blue-green) due to the selective absorption properties of seawater column. Therefore a photograph taken underwater would show the "real" situation rather than what you think you see.

The problem now arises as to whether fish brains compensate in a similar way to that of man. It is more probable that in fishes the brain does not compensate to the same extent, as they never encounter "full daylight" underwater. But they may have a mechanism to compensate for the changes in light quality due to varying depth and water quality that they may encounter.

Assuming that any compensation by fish brains if it occurs, is small, then "daylight" photographic evidence may be thought of as a "fishes eye view". Thus a camera is a very useful instrument in this form of fishing gear research.

A4 Correlation Coefficient

Correlation is concerned with the degree of relationship between two variables.

Taking n pairs of observations of X and Y; they can be plotted against each other to give a "Scatter diagram". From which a rough idea of how the variables X and Y are related.

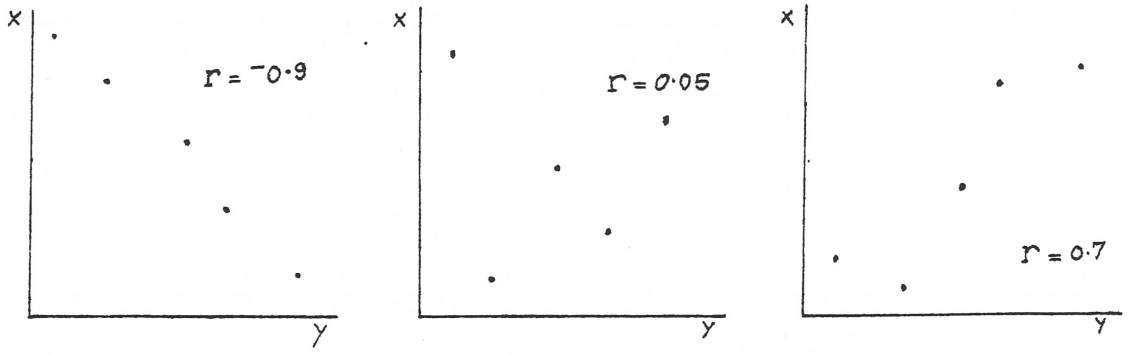
The sample correlation coefficient (r) is used to indicate any linear relationship

where:-

$$r = \frac{\Sigma XY - (\Sigma X \Sigma Y)/n}{\sqrt{(\Sigma X^2 - (\Sigma X)^2/n)(\Sigma Y^2 - (\Sigma Y)^2/n)}}$$

Values of r vary between -1 and +1. A value of r = 1 indicates a perfect linear relationship between the sample values of X and Y, with Y increasing as X increases. A value of r = -1 indicates a perfect linear relationship but with one variable increasing as the other decreases. A value of r = 0 indicates no linear relationship between X and Y.

In practice r is never equal to 1 or -1 but may approach these values if correlation is good.



The underlying assumptions for the correlation coefficient are:-

(1) Both samples, X and Y, are completely random and independent;

(2) The underlying distribution of the variables, X and Y, need not be normal but should be the same for both variables;

(3) The variance of Y is the same for all values of X and vice-versa.

A test of whether a sample correlation coefficient (r) is significantly different from 0 can be made using Table 10, Murdoch and Barnes. The degrees of freedom of the correlation coefficient are ν = DF = n-2 where n is the number of pairs.

Ignoring any minus signs, the calculated sample correlation coefficient r is compared with the tabulated value at n-2 D.F. and desired significance level (given in top row).

If $|r|>$ tabulated value, then the correlation coefficient is significantly different from 0. e.g. for n=8, D.F.=6 the calculated correlation coefficient (r) would have to be greater than 0.7067 to be significant at a 5% level.

With small samples any correlation might tend to be hidden and appear insignificant. With large samples any underlying correlation should tend to show through. Even in large samples where a good correlation might be evident it is not proof that there is actually any true dependence between the results and the resulting outcome may be purely the result of a third factor which influences both.

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References

Ali, M.A. & Wagner, H.J. (1975) Visual Pigments : Phylogeny and Ecology. In 'Vision in Fishes' (ed. Ali et al) pp 481-516. Plenum Press.

Amano, M. (1957) The features and use of "Anilan" fishing nets. In 'Modern Fishing Gear of the World'. F.A.O. Fishing News (Books) Ltd., London, April 1959, pp 150-151.

Andreev, N.N. (1955) Some problems in the theory of the capture of fish by gill nets. Proceedings of the All-Union Scientific Research Institute of Sea Fisheries and Oceanography, Vol. XXX, 1955, pp 109-127. Translated by Central Office of Information, London; for Ministry of Agriculture, Fisheries and Food. Fisheries Laboratory, Lowestoft, 1957.

Andreev, N.N. (1962) Handbook of fishing gear and its rigging. (Translated from Russian). Israel Programme for Scientific Translation, Jerusalem, 1966, p 67.

Angelsen, K. & Huse, I. (1979) Qualitative contrast comparison of differently coloured gill nets. In C.M. 1979/B:20 Fishing Technology Committee. ICES.

Aslanova, N.E. (1958) A study of the behaviour of fishes in the zone of action of fishing gear. Trudy VSES Nauchno-issled. Inst. Morsk ryb Khoz Okeanogr., 36, 33-51. (Translation by Fisheries Laboratory, Lowestoft, 1963).

Baranov, F.I. (1924) The effect of the colour of nets on the success of fishing. Byulletin Rybnogo Khozyaistra No. 21-22, 1924. In 'Selected works on fishing gear; Vol. II: Theory and practice of commercial fishing'. (Translated from Russian by E. Vilim). Israel Programme for Scientific Translation, Jerusalem, 1977, pp 275-280.

Blaxter, J.H.S. (1970) 2 Light: 2.3 Animals: 2.32 Fishes. In 'Marine Ecology, Vol. 1, Part I, Ch. 2, pp 213-285. (Ed. O. Kinne). Wiley Interscience.

Blaxter, J.H.S. (1975) Do fish have an absolute sense of light intensity? In 'Vision in Fishes' (Ed. Ali et al), pp 719-729. Plenum Press.

Blaxter, J.H.S., Parrish, B.B. & Dickson, W. (1963) The importance of vision in fish reaction to drift nets and trawls. In 'Modern Fishing Gear of the World: Book 2'. FAO 1964, pp 529-536. (FAO) Fishing News (Books) Ltd.

Blaxter, J.H.S. & Parrish, B.B. (1965) The importance of light in shoaling, avoidance of nets and vertical migration by herring. J. Cons. Perm. Int. Explor. Mer. 30 (1), 40-57, Copenhague, Decembre 1965.

Brandt, A. Von. (1957) Method of testing resistance of net materials to micro-organisms. In 'Modern Fishing Gear of the World'. F.A.O. Fishing News (Books) Ltd., London, April 1959, pp 133-136.

Brandt, A. Von. (1972) Fish catching methods of the world. Fishing News (Books) Ltd. pp 204-214.

Burgess, J. (1971) Drift, gill and ray netting. Bridport Gundry Ltd.

Burgess, J. (1980) Tangle net colouring. Fishing News, Feb. 1st, 1980, p 16.

Dartnall, H.J.A. (1975) Assessing the fitness of visual pigments for their photic environment. In 'Vision in Fishes' (Ed. Ali et al) pp 543-563. Plenum Press.

Denton, E.J. & Nicol, J.A.C. (1965) Direct measurements on the orientation of the reflecting surfaces in the tapetum of Squalus acanthias, and some observations on the tapetum of Acipenser sturio. J. Mar. Biol. Ass. U.K., 45, 739-742.

Denton, E.J. & Nicol, J.A.C. (1966) A survey of reflectivity in silvery teleosts. J. Mar. Biol. Ass. U.K., 46, 685-722.

Duntley, S.Q. (1962) Underwater visibility. In 'The Sea Vol. I', pp 452-455. (Ed. M.N. Hill). John Wiley, London.

Fridman, A.L. (1969) Theory and design of commercial fishing gear. (Translated from Russian). Israel Program for Scientific Translation, Jerusalem, 1973.

Gazey, B.K. (1970) Visibility & resolution in turbid waters. Underwater Science & Technology Journal, 2 (2), 105-115.

Gruber, S.H. (1975) Duplex vision in the elasmobranch: Histological, Electrophysiological and Psychophysical evidence. In 'Vision in Fishes' pp 525-540. (Ed. Ali et al). Plenum Press.

Hamley, J.H. (1975) Review of gill net selectivity. J. Fish. Res. Bd. Can., 32, 1943-1969.

Hemmings, C.C. (1965) Factors influencing the visibility of objects underwater. In 'Light as an ecological factor' (Ed. Bainbridge, Evans & Rackham). Symposium of the Br. Ecological Society, Cambridge, March 1965, pp 359-374. Blackwell Scientific Publ., Oxford.

Hemmings, C.C. & Lythgoe, J.N. (1964) Better visibility for divers in dark waters. Triton, 9, 28-31.

Hemmings, C.C. & Lythgoe, J.N. (1965) The visibility of underwater objects. In 'Symposium of Underwater Ass., Malta', 1965, pp 23-30.

Hemmings, C.C. & Lythgoe, J.N. (1967) Polarized light and underwater vision. Nature, 213, 893-4.

I.C.I. Ltd. (1957) "Terylene" polyester fibre and its relation to the fishing industry. In 'Modern Fishing Gear of the World'. F.A.O. Fishing News (Books) Ltd., London, April 1959, pp 43-54.

Inoue, N., Nishizawa, S., Tamukai, K. & Kudo, T. (1958) Studies on the visual range of net twines in water - 1. On the relation between the visual range of net twines and the turbidity of surrounding water. Bull. Jap. Soc. Scient. Fish., 24 (6 & 7), 501-506. (English summary)

Jerlov, N.G. (1965) Aspects of light measurement in the sea. In 'Light as an ecological factor' (Ed. Bainbridge, Evans & Rackham). Symposium of the Br. Ecological Society, Cambridge. March 1965. pp 91-98. Blackwell Scientific Publ., Oxford.

Jerlov, N.G. (1968) Optical oceanography. Elsevier Publishing Co. Amsterdam.

Jerlov, N.G. (1976) Marine optics. Elsevier Sc. Publishing Co. Amsterdam.

Kanda, K., Koike, A. & Ogura, M. (1958) The study on the colour of fishing nets: 1, Observations on the passage of fish through coloured nets. 2, Behaviour of fish schools in the neighbourhood of a coloured net. 3, Effect of the depth of colour of the net on the behaviour of a fish school near the net. Bull. Jap. Soc. Scient. Fish., 23, 612-624. (English summary).

Kennedy, W.A. (1951) The relationship of fishing effort by gill nets to the interval between lifts. J. Fish. Res. Bd. Can., 8 (4), 264-274.

Klust, G. (1957) The efficiency of synthetic fibres in fishing, especially in Germany. In 'Modern Fishing Gear of the World'. F.A.O. Fishing News (Books) Ltd., London, April 1959, pp 139-146.

Klust, G. (1973) Netting materials for fishing gear. Publ. Fishing News (Books) Ltd., West Byfleet, England (173 pages)

Kodak (1978) Technical information No. 1140. Kodak Ektachrome 400 film (Daylight)/5074/6074. 7-25-78, pp 1-7.

Koike, A. (1958) Comparative efficiency of differently coloured gill net in the North Sea salmon fishing. Bull. Jap. Soc. Scient. Fish., 24 (1), 9-12. (English summary).

Koike, A., Kanda, K. & Ogura, M. (1958) A preparative study with trout for the salmon gill net. Bull. Jap. Soc., Scient. Fish., 24 (1), 5-8. (English summary).

Larkins, H.A. (1963) Comparison of salmon catches in monofilament and multifilament gill nets (Part 1). Comml. Fish. Rev., 25 (5), 1-11.

Larkins, H.A. (1964) Comparison of salmon catches in monofilament and multifilament gill nets (Part 2). Comml. Fish. Rev., 26 (10), 1-7.

Levy, H. (1957) Discussion on net preservation. In 'Modern Fishing Gear of the World'. F.A.O. Fishing News (Books) Ltd., London, April 1959, p 138.

Lythgoe, J.N. (1965) Visual pigments and underwater vision. In 'Light as an ecological factor' (Ed. Bainbridge, Evans & Rackham). Symposium of the Br. Ecological Society, Cambridge, March 1965, pp 375-391. Blackwell Scientific Publ., Oxford.

Lythgoe, J.N. (1975) Problems of seeing colour underwater. In 'Vision in Fishes' (Ed. Ali et al). pp 619-634. Plenum Press.

Lythgoe, J.N. (1978) Underwater vision. In 'British Sub Aqua Club Diving Manual, 10th Edition'. Eaton Publications, London.

Manteifel, B.P., Rodakov, D.V., Nikonorov, I.V. & Treschev, A.I. (1967) Main trends and some results of fish behaviour studies in the U.S.S.R. (E/48). In F.A.O. Fisheries Report No. 62, Vol. 3, Oct. 1967, pp 809-814. F.A.O.

Margetts, A.R. (1967) Comparative and experimental fishing as methods for studying fish behaviour in the natural environment (R/6). In F.A.O. Fisheries Report No. 62, 2, pp 131-138.

Molin, G. (1957) Tests with nylon fishing tackle in Swedish inland fisheries. In 'Modern Fishing Gear of the World'. F.A.O. Fishing News (Books) Ltd., London, April 1959, pp 156-158.

Munz, W.R.A. (1975) Visual pigments and the environment. In 'Vision in Fishes'. (Ed. Ali et al) pp 656-578. Plenum Press.

Murdoch, J. & Barnes, J.A. (1970) Statistical tables, for Science, Engineering, Management and Business Studies (2nd ed.). Macmillan, London.

Murphy, G.I. (1959) Effect of water clarity on Albacore catches. Limnol. Oceanogr., 4, 86-93.

Nicol, J.A.C. (1963) Luminescence in animals. Endeavour, 22, 37-41.

Nicol, J.A.C. (1967) The biology of marine animals. Ch. 8, pp 302-361. Pitman & Son, London.

Nikonorov, I.V. (1973) Interaction of fishing gear with fish aggregations. (Translated from Russian). Israel Program for Scientific Translation, Jerusalem, 1975. pp 204-214.

Nomura, M. (1957) On the behaviour of fish schools in relation to gill nets. In 'Modern Fishing Gear of the World'. F.A.O. Fishing News (Books) Ltd., April 1959, pp 550-552.

Nomura, M. (1961a) Studies on gill nets - 1. Performance of gill nets and reaction of fish to the net. Bulletin of Tokai Regional Fisheries Research Laboratory, Tokyo, Japan. (30), 9-56, March 1961. (English summary).

Nomura, M. (1961b) Fish behaviour in relation to drift and bag nets. F.A.O. Fisheries Report No. 62, 3, Oct. 1967.

Park, Y.J. & Park, M.S. (1962) Visibility of webbing dyed with several kinds of colour under the ocean. Bulletin of Fisheries College, University of Pusan, VI, 7-10.

Parrish, B.B. (1969) A review of some experimental studies of fish reactions to stationary and moving objects of relevance to fish capture processes. R/12. F.A.O. Fish. Rep., 62 (2), 233-245.

Perlon-Warenzeichenverband, E.V. (1957) The technological characteristics of Perlon for fishing equipment. In 'Modern Fishing Gear of the World'. F.A.O. Fishing News (Books) Ltd., London, April 1959, pp 34-42.

Du Pont, E.I. de Nemours & Co. Inc. (1957) Synthetic fibres in the fishing industry. In 'Modern Fishing Gear of the World'. F.A.O. Fishing News'. F.A.O. Fishing News (Books) Ltd., London, April 1959, pp 147-149.

Protasov, V.R. (1968) Vision and near orientation of fish. (Translated from Russian). Israel Program for Scientific Translation, Jerusalem, 1970.

De Reuck, A.V.S. & Knight, J. (Ed.) (1965) Colour Vision. A C.I.B.A. Foundation Symposium.

Reuter, J. (1957) Discussion on net preservation. In 'Modern Fishing Gear of the World.' F.A.O. Fishing News (Books) Ltd., London, April 1959, p 137.

Richter, H.U. (1962) Underwater Photography. In 'Photography for the Scientist', Ch. 9, pp 385-390. (Ed. C.E. Engel). Academic Press.

Ruperti, A. (1957) Rot-resistant fishing nets by the "Arigal" process. In 'Modern Fishing Gear of the World'. F.A.O. Fishing News (Books) Ltd., London, April 1959, pp 123-124.

Sandoz, Ltd. (1957) Application of acetylated cellulose for fishing gear. In 'Modern Fishing Gear of the World'. F.A.O. Fishing News (Books) Ltd., London, April 1959, pp 125-127.

Steinberg, R. (1962) Die Fangigkeit von Kiemennetzen für Barsch und Plötze in Abhängigkeit von den Eigenschaften des Netzmaterials, der Netzkonstruktion und der Reaktion der Fische. (English summary). Arch. Fischereiwiss 12, 173-230.

Steinberg, R. (1963) Monofilament gill nets in freshwater experiment and practice. In 'Modern Fishing Gear of the World; Book 2'. F.A.O. Fishing News (Books) Ltd., June 1964, pp 111-114.

Stell, W.K. (1975) Structural studies of functional pathways in goldfish retina. In 'Vision in Fishes'. (Ed. Ali et al). Plenum Press. pp 81-90.

Sundnes, G. (1964) The effect of gear on spawning cod. World Fishing 13 (7), 59-60.

Takayama, S. & Shimozaki, Y. (1957) Development of fishing net and rope preservation in Japan. In 'Modern Fishing Gear of the World'. F.A.O. Fishing News (Books) Ltd., London, April 1959, pp 113-122.

Tansley, K. (1965) Vision in vertebrates. Science Paperbacks & Chapman & Hall Ltd.

Tran-Van-Tri & Ha-Khac-Chu. (1963) Nylon monofilament in the Viet-Nam fisheries. In 'Modern Fishing Gear of the World; Book 2'. F.A.O. Fishing News (Books) Ltd., London, June 1964, pp 108-110.

Tyler, J.E. (1968) The Secchi Disc. Limnol. Oceanogr., 13, 1-6.

Walker, T. (1980) A correction to the Poole & Atkins Secchi disc/ light-attenuation formula. J. Mar. Biol. Ass. U.K. 60, 769-771.

Williams, J. (1970) Optical properties of the sea. United States Naval Institute Press, Annapolis, Maryland.

Williams, J. (1973) Oceanographic instrumentation. Naval Institute Press, Annapolis, Maryland.

Woods, J.D. & Lythgoe, J.N. (1976) Underwater Science. Oxford University Press, London.

Zyznar, E.S. (1975) Theoretical considerations about Tapeta lucida. In 'Vision in Fishes'. (Ed. Ali et al), pp 305-312. Plenum Press.

Further reading

Brandt, A. Von. (1967) Application of observations on fish behaviour for fishing methods and gear construction (R/8). In F.A.O. Fisheries Report 62, 2, pp 171-191.

Gullard, J.A. (1967) Statistical aspects of comparative fishing trails. In 'Rep. FAO/UNDP (TA),'(2271-11); pp 349-350.

Hester, F.J. (1968) Visual contrast threshold of goldfish (Carassius auratus). Vision Res., 8, 1315-1336.

Hester, F.J. & Taylor, J.H. (1965) How tuna see a net. Commer. Fish. Rev. 27 (3); 11-16.

High, W.L. (1969) Scuba diving, a valuable tool for investigating the behaviour of fish within the influence of fishing gear (E/2). In F.A.O. Fisheries Report 62, 2, pp 253-267.

Jester, D.B. (1973) Variations in catchability of fishes with colour of gill nets. Trans. Am. Fish. Soc., 102, 109-115.

Legett, W.C. & Jones R.A. (1971) Net avoidance behaviour in American shad, (Alosa sapidissima) as observed by ultrasonic tracking techniques. J. Fish. Res. Bd. Can., 28, 1167-1171.

Lythgoe, J.N. (1979) The ecology of vision. Oxford University Press, 1979.

Molin, G. (1958)* Färg-Fisklighet I; Svensk Fiskeritidsskrift, pp 114-118 (Swedish)

Molin, G. (1959)* Färg-Fisklighet II; Svensk Fiskeritidsskrift, pp 77-80 (Swedish)

Molin, G. (1960)* Farg-Fisklighet III; Svensk Fiskeritidsskrift, pp 89-92 (Swedish)

Molin, G. (1961)* Farg-Fisklighet IV: Svensk Fiskeritidsskrift, pp 58-62 (Swedish)

Tsuda, R. & Inoue, N. (1973) Study on the underwater visibility of net twines by the human eye - III Estimation of the threshold of brightness contrast. Bull. Jap. Soc. Sci. Fish. 39, 253-264.

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