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VISUAL ACUITY AND OLFACTORY SENSITIVITY IN THE SWORDFISH (*XIPHIAS GLADIUS*) FOR THE DETECTION OF PREY DURING FIELD EXPERIMENTS USING THE SURFACE LONGLINE GEAR WITH DIFFERENT BAIT TYPES.

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SUMMARY

During a total of 20 sets carried out on board a surface longliner, the different degrees of effectiveness obtained in the capture of swordfish were evaluated using 5 different bait types (natural, artificial and mixed). The results point to substantial and significant differences in the CPUEs obtained among the different bait types tested to catch swordfish. However, the results show few mean differences that were not statistically significant between the CPUEs obtained using natural bait (control) or mixed bait consisting of artificial bait on the outside -which in itself was of null effectiveness- into which was inserted a piece of natural bait, concealed from view. Both types of bait (control and mixed) were effective in the capture of swordfish despite the differences in constitution and properties. On the basis of these results, it is possible to make an indirect assessment of the importance of visual and odor stimuli in the swordfish to detect and carry out the final attack on its prey. Odor was found to be the key element in this process.

RÉSUMÉ

Au cours de 20 opérations réalisées à bord d'un palangrier de surface, divers niveaux d'efficacité obtenus dans la capture de l'espadon ont été évalués à l'aide de cinq types d'appât différents (naturel, artificiel et mixte). Les résultats indiquent des différences considérables et significatives dans les CPUE obtenues entre les divers types d'appât testés pour capturer l'espadon. Néanmoins, les résultats suggèrent peu de différences moyennes, statistiquement peu significatives, entre les CPUE obtenues en usant un appât naturel (contrôle) ou un appât mixte composé d'appât artificiel à l'extérieur, d'aucune efficacité en soi, auquel a été ajouté dans son intérieur une portion non visible d'appât naturel. Les deux types d'appât (contrôle et mixte) se sont avérés efficaces pour la capture de l'espadon en dépit de leurs différences de constitution et de propriété. Les résultats permettent d'évaluer indirectement l'importance pour l'espadon des stimulations visuelles et olfactives pour détecter et attaquer sa proie. L'odeur s'est avéré être l'élément clef dans ce processus.

RESUMEN

Durante un total de 20 lances realizados a bordo de un palangrero de superficie fueron valoradas las distintas eficacias obtenidas en la captura de pez espada usando 5 diferentes tipos de cebo (naturales, artificiales y mixtos). Los resultados sugieren diferencias considerables y significativas de la CPUE obtenida entre los distintos tipos de cebo ensayados para la captura del pez espada. Sin embargo, los resultados sugieren escasas diferencias medias, estadísticamente no significativas, entre la CPUEs obtenidas usando un cebo natural (control) o un cebo mixto compuesto de cebo artificial en el exterior, de nula eficacia por si mismo, al que se le añadía en su interior una porción no visible de cebo natural. Ambos tipos de cebos (control y mixto) se mostraron eficaces para la captura del pez espada pese a su diferente constitución y propiedades. Los resultados permiten valorar indirectamente la importancia para el pez espada de los estímulos visuales y del odor para la detección y ataque final a sus presas, sugiriendo al olor de la presa como un elemento clave en este proceso.

KEY WORDS

Swordfish, Visual acuity, Olfactory sensitivity, Bait, CPUE

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1. Introduction

Large pelagic teleosts such as marlins, swordfish and tuna are active migrators and predators that depend largely on their vision to catch their prey and thereby fulfill their huge energy requirements. However, the detection of the prey and the final attack are based on a complex system of sensations involving multiples senses. These animals also appear to have a well-developed sense of smell which may be essential in helping them meet these feeding needs. Several authors have suggested that large fishes are endowed with greater visual acuity than smaller fishes (Kawamura *et al*. 1981, cited by FRITSCHES, *et al*. 2003), and they also describe specific structures and mechanisms that would explain this greater or superior visual acuity (Tamura & Wisby, 1963; Fritsches *et al*. 2000, 2003, 2005). According to this rule, large teleosts and elasmobranchians that live in pelagic-oceanic habitats should generally have sharper visual acuity than many other fish species. The large size of the eyes in marlins, swordfish and tuna, coupled with their well-developed associated visual systems, have therefore been put forth as key elements suggesting that vision is probably the most important sense used by these pelagic species to detect and catch their prey (Kawamura *et al*. o.c.). If indeed this is the case, it would be especially true in the swordfish, whose warm eyes are enormous, several times superior in vision than other fishes with eyes at the same temperature as the surrounding waters and adapted to both daytime predation-but in the darkness of the relatively deep layers at depths of hundreds of meters- as well as nocturnal predation in the layers nearer to the surface, as would be suggested by the behavior observed using electronic pop-up tags (Matsumoto *et al*. 2003).

Later studies have played down, to some extent, the importance of visual acuity for this purpose, and suggest a surprisingly low visual resolution in the blue marlin given the absolute size of the eyes of this species, indicating that the marlin eye is specifically adapted to cope with low light levels encountered during diving, which means that billfish would probably have one of the highest absolute optical sensitivities of the teleost fishes (Fritsches *et al.* 2003). The above authors explain that because the pupil of fish does not constrict, one of the strategies of the billfish to improve optical sensitivity is to enlarge its photoreceptors. Other research has also reported that the average accommodation in the direction of the visual axis in some of these species is considered to be approximately between 2-4 dioptres, i.e., from infinity to 50-25 cm (Tamura & WISBY o.c.), which would suggest, a priori, that while the location of the prey might be basically visually-based, the final decision of whether or not to attack a potential prey, however, might not be made preferentially on the basis of visual stimuli, but rather on a combination of stimuli coming in from several senses, as occurs in most animals.

The olfactory response of large pelagic teleosts to prey odors was also studied in some large pelagic teleost species such as the yellowfin tuna (Atema *et al*. 1980). These authors conclude that this species can detect and distinguish between odors of intact prey organisms, responding to the odor quality of various prey rinses with different amino acid profiles, suggesting that the odor quality determined the response intensity. The chemical fraction of natural prey odors and synthetic mixtures of amino acids was described by these authors to be less effective than whole natural rinses. These authors also suggest that the olfactory system of tuna probably forms “chemical search images” which may be modifiable depending on the abundance of prey. The physiological similarity between the swordfish and some tuna such as the bigeye tuna (*Thunnus obesus*) points to the possibility of similar evolutionary adaptations and behaviors in some aspects of the last two species (Brill, *pers. com.)*.

Most of the research dealing with the study of these aspects has been conducted on specimens held in captivity or on the basis of theoretical, histological, optical and electrophysiological studies. In this investigation, in contrast, we took advantage of some experiments carried out in the field that were originally designed to evaluate the effectiveness of using different types of bait (natural vs artificial) for the commercial capture of the swordfish with surface longline. A comparison of the results obtained in this experiment may help to interpret earlier studies carried out using other strategies, or to design future experiments, offering information of interest on the importance given by the swordfish to visual and odor stimuli when locating its prey among the wide variety available and making the final decision to attack.

2. Material and methods

A total of 20 sets were carried out between November and December, 1997 in the temperate waters of the NE Atlantic (SST ranging between 21.0 and 24.5ºC) at positions covering between 22º 11’N and 23º 50’N latitude and between 16º 59’W and 20º 08’W longitude. The experiment was conducted using a traditional Spanish type surface longline gear in which the main line is kept at a specific depth by the joint action of the weights and floats. Hanging from the main line are branch lines which are tied with their respective hooks. (Hoey *et al.* 1988).

Overall during the survey 5 different types of bait were tested: Bait 1: mackerel (natural bait and control bait). Bait 2: plastic imitation of mackerel. Bait 3: plastic imitation of squid. Bait 4: plastic imitation of mackerel (bait 2) filled inside with a sponge impregnated with sardine oil. Bait 5: plastic imitation of mackerel (bait 2) filled with ½ piece of real mackerel.

The natural mackerel specimens (*Scomber scombrus*) used as bait weighed around 350 grs each **(Photo 1)**. Mackerel is one of the natural baits most commonly used by the Spanish surface longline fleet as a whole and it was considered as a "control" bait versus the other bait types tested since mackerel has proven to be highly effective in the capture of swordfish, especially in temperate waters. Artificial bait 2 attempted to be a plastic imitation of the mackerel, although it had a brilliant white coloring that did not imitate the natural color; it was slightly translucent and made from a type of hollow flexible plastic with holes for the hook and evacuation of water **(Photo 2)**. Therefore, bait 2 only bore a slight resemblance to mackerel in its silhouette; it did not resemble the natural mackerel in color in any way and it lacked any type of olfactory stimulus to be considered as a potential prey. Artificial bait 3 was a plastic imitation of a medium-sized squid that attempted to mimic its natural coloring **(Photo 3)**. Bait 4 consisted of type 2 bait, which was filled inside with a sponge impregnated with a type of oil obtained from sardine by-products, endowing it with a potential capacity for attraction by its odor **(Photo 4)**. Bait 5 was designed during the trip in view of the fair to poor results obtained during the first sets with the other types of bait tested. It comprised a type 2 bait which was filled inside with approximately half of a mackerel concealed from view, which made it possible to make an indirect estimation of the importance of the olfactory stimulus in the catch strategy of this species as compared to the plastic bait (bait 2) which did not offer this stimulus, or compared to the natural bait (bait 1). Thus, bait 5 was semi-artificial, fashioned from baits 1 and 2. In view of the positive experiments with the semi-artificial bait 5, we decided to include it in the experiment from set 8 to set 20 (13 sets). The use of the different types of bait over the course of the study was partially conditioned by their availability and the preliminary results obtained. Baits 1 and 2 were used in all the sets carried out.

The longline was structured into different sections or bridges separated by colored buoys to facilitate their identification. For the purpose of minimizing other possible factors that might influence the catchability of the gear-bait and due to the limited number of sets available to conduct this experiment, the different bait types were set up on the longline within each set. Sections using bait 1 natural (control) were alternated with randomly placed sections with other alternative baits. In this way in one set, different bait types were tested, but they were always separated by a section using the natural bait. To avoid the possible positive influence of natural bait on the effectiveness of the other baits located on adjacent sections, these sections were separated, leaving 4 branch lines without hooks and bait, which translates to a separation of around 124 m between these consecutive sections-bait.

The number of sections let out per set was 23 or 24, which amounts to a total of roughly 2200 or 2300 hooks per set or fishing day. The disposition of the different bait types on the gear varied mid-way through the trip. In this way two general schemes were tested according to the number of sections and the success obtained depending on the bait type used, which led to the definition of two types of structures or gear disposition and bait type. Disposition (A), with 23 sections: Bait 1 = 12 sections, 1152 hooks, 52%. Bait 2 = 4 sections, 384 hooks, 17%. Bait 3 = 4 sections, 384 hooks, 17%. Bait 4 = 3 sections, 288 hooks, 13%. Disposition (B), with 24 sections: Bait 1 = 11 sections, 1056 hooks, 46%. Bait 2 = 4 sections, 384 hooks, 17%. Bait 5 = 9 sections, 864 hooks, 37%. The sections were arranged on the longline with the different bait types by randomly alternating their position.

Catch data (C) in number of individuals (n) and round weight (w) and nominal effort in thousands of hooks (f) were obtained per set (s) and bait type (b). The Catch per unit of effort (CPUE) per set and bait type was defined as: $CPUEn_{sb} = Cn_{sb} / f_{sb}$, and $CPUEw_{sb} = Cw_{sb}/f_{sb}$. In order to improve the standardization of the CPUE, logarithmic transformations LN(CPUE+1)were carried out and analyzed by means of GLM to detect the significance of the bait factor in the CPUE obtained. ANOVA Multiple Range Tests were also used to detect significant differences between the different mean CPUE pair combinations obtained from the different bait types tested.

3. Results and discussion

During the 20 sets a total number of 45,792 hooks were set, from which 22,464, 7,392, 2,880, 2,784 and 10,272 hooks were used for each bait type tested, from 1 to 5 respectively. **Table 1** summarizes the basic statistics for the CPUE resulting from each bait type used. **Figure 1** shows the box plots of the CPUE for each bait type used. The mean CPUE values would point to bait 1 (natural or control) as the most effective, although it showed effectiveness values very similar to those obtained using bait type 5, both of which were followed by bait type 4, which was highly variable in effectiveness and bait 3, the latter two being clearly less effective. Bait 2 had practically null effectiveness in most of the sets, contrasting sharply with the effectiveness of bait 5 which had the same outer appearance.

The execution of only 20 sets during the experiment limits the significance of the results obtained and affects the normality of the data observed. Nonetheless, the results point to significant differences in the CPUEs depending on the bait type used. The F-tests of the GLM analyses carried out for LN (CPUEn+1) and LN (CPUEw+1) show significant differences ($p<0.01$) between the mean CPUEs obtained according to the bait type used. The bait type and set would explain 88% and 86 % of the variability observed in the CPUE in number and weight, respectively, with the bait type being the significant factor ($p<0.01$) that is clearly the most important in helping to explain the variability in the CPUE.

The ANOVA Multiple Range Test, depending on the bait type, detected significant differences in the means between most of the paired values of LN (CPUEn) or LN (CPUEw), which would suggest that there are significant differences between means at a 95% confidence limit in most of the pairs, except for pairs 1-5 and 2-3, (**Table 2**). Baits types 1 and 5 tested during this limited experiment both proved to be quite effective in catching swordfish, but we were surprised to find that they did not show statistically significant differences when compared with each other, despite their differences in constitution and properties. Bait type 4 was moderately effective, particularly in some sets and baits 2-3 were found to be highly ineffective and showed no significant differences when compared with each other.

The results obtained with baits 1 and 5 are especially noteworthy, if they are compared, in turn, with the results obtained using bait type 2. As mentioned earlier, bait 2 proved to be completely useless in the capture of swordfish, without being able to catch practically any fish of this species. However, this situation changed drastically when bait 5 is used. Bait 5 is basically bait 2 but filled with a piece of mackerel, concealed from view. It might therefore be assumed that the difference between the CPUEs of bait 2 and bait 5 might be almost exclusively attributable to the absence or presence of odor between the two baits. There may be other factors that have not been taken into account that would affect –to a lesser extent- the CPUEs obtained with these two bait types, such as the different degree of floatability between the sections, since the weight of bait type 5 is less that of natural bait 1. Moreover, the plastic mackerel used in bait 5 would serve to protect the fragment of natural bait placed inside from small predator species, thus preventing, in some specific cases, the fragment of natural bait from being devoured in just a few minutes before being effectively used to catch swordfish. Nevertheless, the latter two factors discussed are considered to have relatively small or negligible effects on the catchability or CPUE obtained.

It is likely that both bait 2 and bait 5 are initially detected by the swordfish by sight or perhaps a combination of stimuli, yet artificial bait 2 would not be attacked in the end as it lacked any recognizable odor. Bait type 5, on the other hand, was attacked with less but similar effectiveness as natural bait type 1. In this experiment, no statistically significant differences between the two bait types were found. Along these lines, previous studies conducted on the yellowfin tuna already suggested that this pelagic species is also capable of detecting small amounts of amino acid rinses consisting of prey odors (Atema *et al*. o.c.), a faculty that the large pelagic sharks are also known to possess (Hueter *et al*. 2004). The conclusions drawn after comparing the results from bait 2 and bait 5 are also corroborated by the positive, although more moderate, effectiveness obtained using bait type 4, which consists of bait type 2, but with the inside filled with oil made from sardine derivatives. This also confirms observations made by other authors when they point to the less effective chemical fractions versus natural prey odors of the natural rinses (Atema *et al*. o.c.). In keeping with this, we must also bear in mind that the sardine is not a prey that is seen frequently in the stomach contents of the swordfish, so the odor of its by-products would probably be only fairly effective as a type of bait, although the swordfish feeds on a wide variety of prey, adapting to local availability and the depths where the fish is found at the time.

The results obtained would suggest that the swordfish's decision to finally attack the prey may be influenced above all by olfactory rather than visual stimuli. These visual stimuli may very well play a major role in the initial detection of its potential prey in the situations on the boundary of light where the swordfish usually lives and feeds, but they may have a much smaller effect than odor in the final decision to attack the prey.

The results serve as a source of motivation to conduct new experiments in the field, applying a greater fishing intensity, under different conditions in the natural environment and using technologies specifically designed for this purpose. Experimental designs aimed at future experiments in conditions of captivity may consider the results presented in this paper. In addition, the results will encourage future research to test baits obtained from by-products and residuals from the fishing industry that are more cost-friendly and have less of a biological impact on the stocks of the species used as natural bait. This alternative has already been tested into practice for the longline fishery of some demersal fishes.

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Table 1. Summary of basic statistics for data (effort in number of hooks, CPUEn and CPUEw) for each bait type (1 to 5) used during the experiment.

Bait type	*Data*	*Effort*	*CPUEn*	*CPUEw*
1	Min.	1056.00	2.84	85.22
1	Mean.	1123.20	14.67	385.58
1	Median.	1056.00	13.26	394.88
1	Max.	1248.00	25.56	617.18
1	Sets.	20	20	20
1	Std. Dev.	82.99	7.14	165.73
1	Sum.	22464.00	----	----
2	Min.	96.00	0.000	0.000
2	Mean.	369.600	0.130	2.083
2	Median.	384.000	0.000	0.000
2	Max.	384.000	2.600	41.660
2	Sets.	20	20	20
2	Std. Dev.	64.399	0.581	9.315
2	Sum.	7392.000	----	----
3	Min.	288.000	0.000	0.000
3	Mean.	360.000	0.975	30.599
3	Median.	384.000	0.000	0.000
3	Max.	384.000	5.200	182.290
3	Sets.	8	8	8
3	Std. Dev.	44.439	1.934	65.078
3	Sum.	2880.000	----	----
4	Min.	288.000	0.000	0.000
4	Mean.	309.333	6.557	180.166
4	Median.	288.000	3.470	121.520
4	Max.	384.000	20.830	503.470
4	Sets.	9	9	9
4	Std. Dev.	42.332	7.849	188.959
4	Sum.	2784.000	----	----
5	Min.	288.00	0.00	0.00
5	Mean.	790.15	13.97	300.14
5	Median.	864.00	11.57	248.84
5	Max.	864.00	31.25	719.90
5	Sets.	13	13	13
5	Std. Dev.	184.47	10.71	252.79
5	Sum.	10272.00	----	----

Table 2. ANOVA . Multiple Range Test for LN(CPUEn+1) and LN(CPUEw+1), by bait type used.

CPUEn. Method: 95% LSD.

Bait type	Number of Sets	Mean value	Homogeneous Groups
2	20	0.064	x
3	8	0.388	x
4	9	1.435	x
5	13	2.346	x
1	20	2.633	x

Contrast	Difference	+ / - Limits
1-2	* 2.568	0.467
1-3	* 2.245	0.618
1-4	* 1.197	0.593
1-5	0.287	0.526
2-3	-0.324	0.618
2-4	* -1.371	0.593
2-5	* -2.282	0.526
3-4	* -1.047	0.718
3-5	* -1.958	0.663
4-5	* -0.910	0.641

* denotes a statistically significant difference between pairs of bait types.

CPUEw. Method: 95% LSD.

Bait type	Number of Sets	Mean value	Homogeneous Groups
2	20	0.188	x
3	8	1.170	x
4	9	3.617	x
5	13	5.026	x
1	20	5.827	x

Contrast	Difference	+ / - Limits
1-2	* 5.640	0.964
1-3	* 4.657	1.276
1-4	* 2.210	1.224
1-5	0.801	1.086
2-3	-0.983	1.276
2-4	* -3.430	1.224
2-5	* -4.839	1.086
3-4	* -2.447	1.482
3-5	* -3.856	1.370
4-5	* -1.409	1.322

* denotes a statistically significant difference between pairs of bait types.

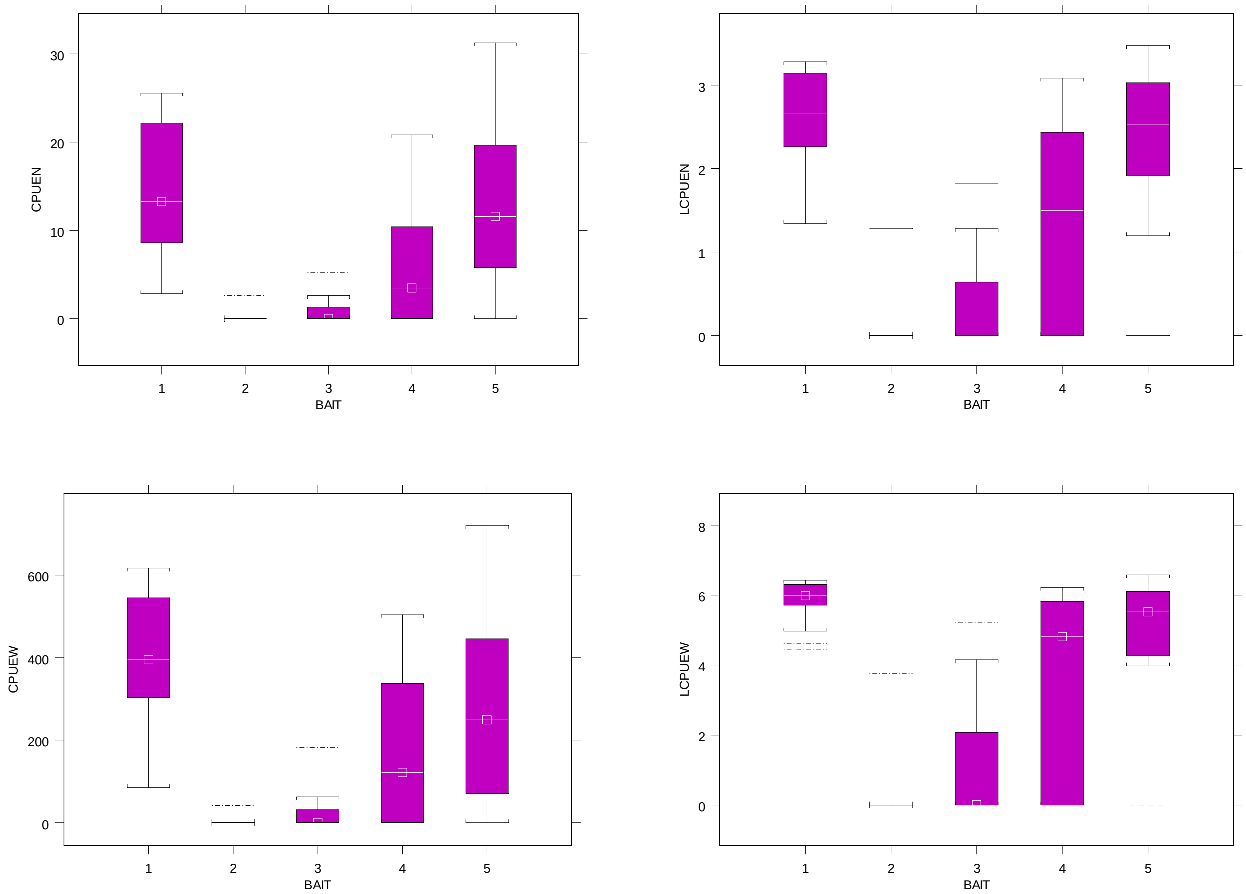

Figure 1. Box plots of CPUEn, CPUEw, and logarithmic transformation of both CPUEs, by bait type used during the survey.

Photo 1. Bait type 1. Mackerel (*Scomber scombrus*) used traditionally as bait in the Spanish swordfish fishery in temperate waters. Hooked mackerel ready to be used during the set.

Photo 2. Bait type 2. Artificial bait or plastic mackerel with holes for expelling water and odor (left). Side opening used to insert other elements to fashion other types of bait tested (right).

Photo 3. Bait type 3. Artificial bait or plastic squid. Disposition of the bait and hooks (left) and the branch line before being used in the set (right).

Photo 4. Bait type 4. Artificial bait consisting of plastic mackerel (type 2) filled with a sponge impregnated with oils derived from the sardine. Configuration of the branch line (left) and process through which it is impregnated with oil prior to use (right).