XXXI Congress and Plenary Assembly, Athens, October 17 - 22, 1988
C.I.E.S.M. Comité Vertébrés Marins et Cephalopodes.

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Preliminary notes on behaviour of a blind-folded free swimming dolphin (Tursiops truncatus, Montagu), performing a target echo location task in a tank.

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Abstract.

A study has been carried out since 1987 by C.N.R.-I.R.PE.M., in collaboration with A.S.W. in Riccione, to find out how a blind-folded, free swimming Tursiops truncatus (Montagu) uses echolocation clicks for searching a target, approaching it and making contact with rostrum (nose).

After a period of training (1987), the dolphin performed 72 sonar searches (Febraury/May 1988), that are the object of the paper.

The experiments have been carried out using a B & K type 8103 hydrophone, arranged 5 cm. above the target, an automatized underwater camera which an operator through a consolle can aim at the moving dolphin, equipments for recording and analysing both acoustic an video signals, properly syncronized. The target is a copper sphere, with an accurate and reliable target strength at 120 KHz. It is the standard target used to calibrate echo-sounders, specialized to estimate size and weight of small pelagic fish, usual prey of tursiopes.
Data collected in the experiments can be analyzed either to investigate the acoustical parameters or the tactical acoustical behaviour of the dolphin. It is the second type of analysis, that is developed in the paper. Three distinct phases in the behaviour of dolphin are identified: (1) The dolphin searches the target untill he locates it acoustically. This phase comprises three basic functions (target detection, target selection and target location) and interests an area up to five meters around the station (searching area). (2) The dolphin approaches acoustically the target, moving along poligonal-like curves. In this phase the target is illuminated by a number of clicks much lower than the expected one. The paper suggests an explanation of this unexpected behaviour, based on the triangulation method. (3) The dolphin attacks the target, moving and rotating the body along descending trajectories. The shape of this trajectories, strongly influenced by the depth of the target, is analysed in the paper. This third phase interests an area close to the target (attacking area).
In the last part of the paper the problems, that the study opens, are illustrated.

PRELIMINARY NOTES ON BEHAVIOUR OF A BLINDFOLDED FREE-SWIMMING DOLPHIN PERFORMING A TARGET ECHOLOCATION TASK IN A POOL

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METHODS

A study has been carried-out since 1987 by the Research National Council (C.N.R.) in Ancona in collaboration with Adriatic Sea World (A.S.W.) in Riccione, to find-out how a blind-folded free-swimming Tursiops truncatus (Montagu) uses echolocation clicks for detecting a target, approaching it and making contact with its rostrum.

After a period of training (1987), the dolphin performed 72 sonar searches (February/ May 1988), that are the objects of discussion.

The experiments have been carried-out using a B&K type 8103 hydrophone arranged 5 cm above the target, an automatized underwater video camera, which an operator through a consolle can aim at the moving dolphin, equipments for recording and analysing both acoustic and video signals, properly synchronized (Figure 1). The target was a copper sphere (30 mm diameter), with target strength of 36 dB ± 0.5 at 120 KHz. It is the standard target used to calibrate the echo-sounders specialized to estimate size and weight of small pelagic fish usual prey of Tursiops.

The pool, the position of the target, the camera during the experiments are illustrated in Figure 2. The experiment was divided in two sessions. A session consisted of two sequences of six 3-trials blocks. In a sequence the target had fixed bearing and horizontal range but six different depths (see Table 1). For each depth a block of 3-trials was carried-out, but there were no evident of dependencies in the depths series. Then the bearing and the horizontal range were changed and a second sequence of trials repeated.

The experiment was conducted using an adult female Tursiops truncatus named Candy, but in the presence of two other adult dolphins. Initially, the three dolphins maintained the station by facing away from the target in front of the trainer. When Candy was blind-folded with eye cups, she turned and performed a sonar search of the target, while the other two animals mantained the station. In the correct trials, that were reinforced with fish, the dolphin acquired the target, approached it, made contact with its rostrum and at a recall signal of the trainer returned to the station. Incorrect trails were not reinforced and did not delay the commencement of the next trail.

Sensory Abilities of Cetaceans
Edited by J. Thomas and R. Kastelein
Plenum Press, New York, 1990

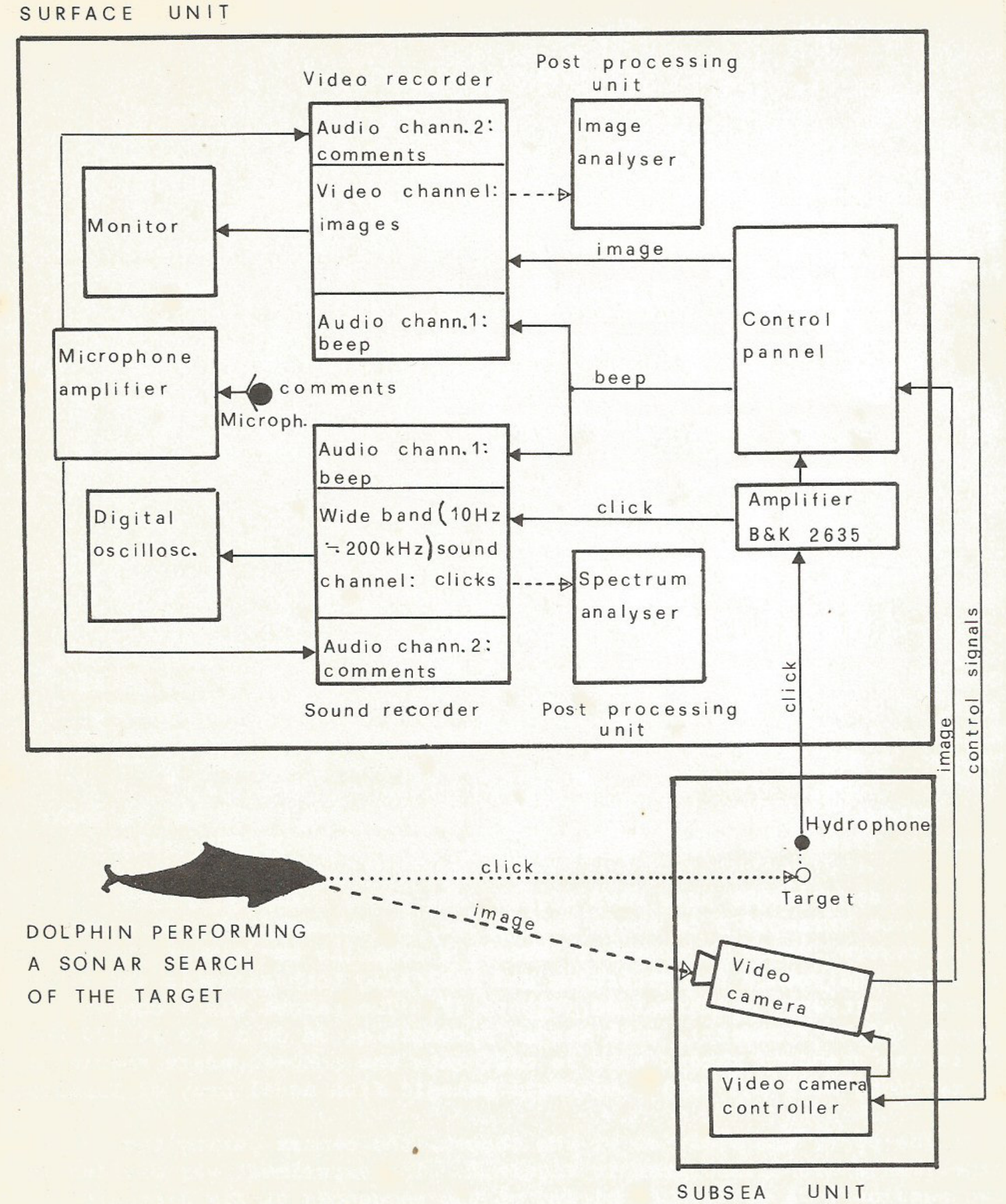

Fig. 1. Block diagram of tracking measuring and processing system. The outputs of the video camera and of the hydrophone are continuously recorded. A special circuit produces an audible signal "beep", whenever a train of clicks hits the hydrophone; it insures the operator that the dolphin is echolocating the target. The "beep" together with the comments of the esperimenter are used to synchronize the video and sound recorders.

SUBJECT OF DISCUSSION

Data collected in the experiment were analyzed to investigate the acoustical parameters of the emitted signals (click waveforms, spectra, click rate) and the tactical acoustical behaviour of the dolphin (method used in searching, tracking and reaching the target).

It is the second aspect of the problem that is the subject of discussion. The tactical acoustic behaviour of the dolphin comprises three phases. In the first phase the dolphin searches the target until it was located. This phase interests a restricted area of the pool up to 5 m around the station, the searching area of Figure 2. In the second phase the dolphin approaches the target, transducing acoustic informations in tracking decisions so as to arrive in the neighbouring of the target, the attacking area of Figure 2. From this area the dolphin attacks the target moving along spiral-like trajectories. However, in this last phase the behaviour of the dolphin strongly depends on the depth of target. This paper focuses mainly on the second phase.

FIRST PHASE: SEARCH FOR THE TARGET

The first problem that the dolphin has to solve is searching for the target. This operation that is performed around the release station, comprises three basic functions.

Target Detection (Figure 3A)

The dolphin must have the capability of scanning the entire tank volume and the ability to extract the "candidate targets" from noise and from reverberation of surface, bottom, sides and corners of the pool. It implies choosing locally appropriate thresholds. Figure 3A illustrates the attitude of the dolphin while he is detecting (and/or selecting) the candidate targets (the target). It is interesting to note that the dolphin in scanning the tank volume, behaved as though he had perceived the different probabilities of changing in the target bearing (a change every 18 trials) and in the target depth (a change every trial). In fact, the bearing angle at which the dolphin pointed the rostrum was dependent on the one immediately preceeding, whereas the entire azimuth sector was scanned in each successive trial.

Target Recognition

Upon completing the search of the acquisition space, the dolphin must decide which detection is most target-like and should be echolocated. Successful recognition of the target involves the unique ability of the dolphin to perform various tests on the detected signals to estimate shape, material, dimensions of the objects and to discriminate the true detection of the target against false detections of the other objects, such as the hydrophone, the cable, the video camera.

Table 1. Position of the Target Referred to a Cylindrical Coordinate System Centered at the Station

Coordinate	Target on the left side	Target on the right side
bearing angle	+ 19 degree	-42 degree
horizontal range	20 m	15.6 m
vertical range or depth	very close to bottom: in mid-water: very close to surface	4.8 m 4 m; 3 m; 2 m; 1 m 0.2 m

Target Location (Figure 3B)

In Figure 3B, taken two seconds after Figure 3A, the dolphin locates the target and estimates the "rostrum-to-target" line of sight vector. The "rostrum-to-target" position vector is perceived by the dolphin as the "error" that he must minimize, during the tracking process, to reach the target. Let $\underline{T}$ and $\underline{S}$ be the "station-to-target" and the "station-to-rostrum" position vectors respectively, expressed with reference to a fixed system of coordinate (Figure 4), then the "rostrum-to-target" vector, at time t_0, is the difference between the vector $\underline{T}$ (the "input" in the dolphin system) and the vector $\underline{S}$ (t_0) (the "output" in the dolphin system):

$$\underline{R}\ (t_0) = \underline{T} - \underline{S}\ (t_0)$$

However, since the rostrum is pointed to the target relative to dolphin body, it is most appropriate expressing $\underline{R}$ (t_0) in the dolphin body coordinate system as illustrated in the Figure 5. The form of the pointing vector (i.e. the rostrum-to-target vector) in the intrinsic coordinate system is given by

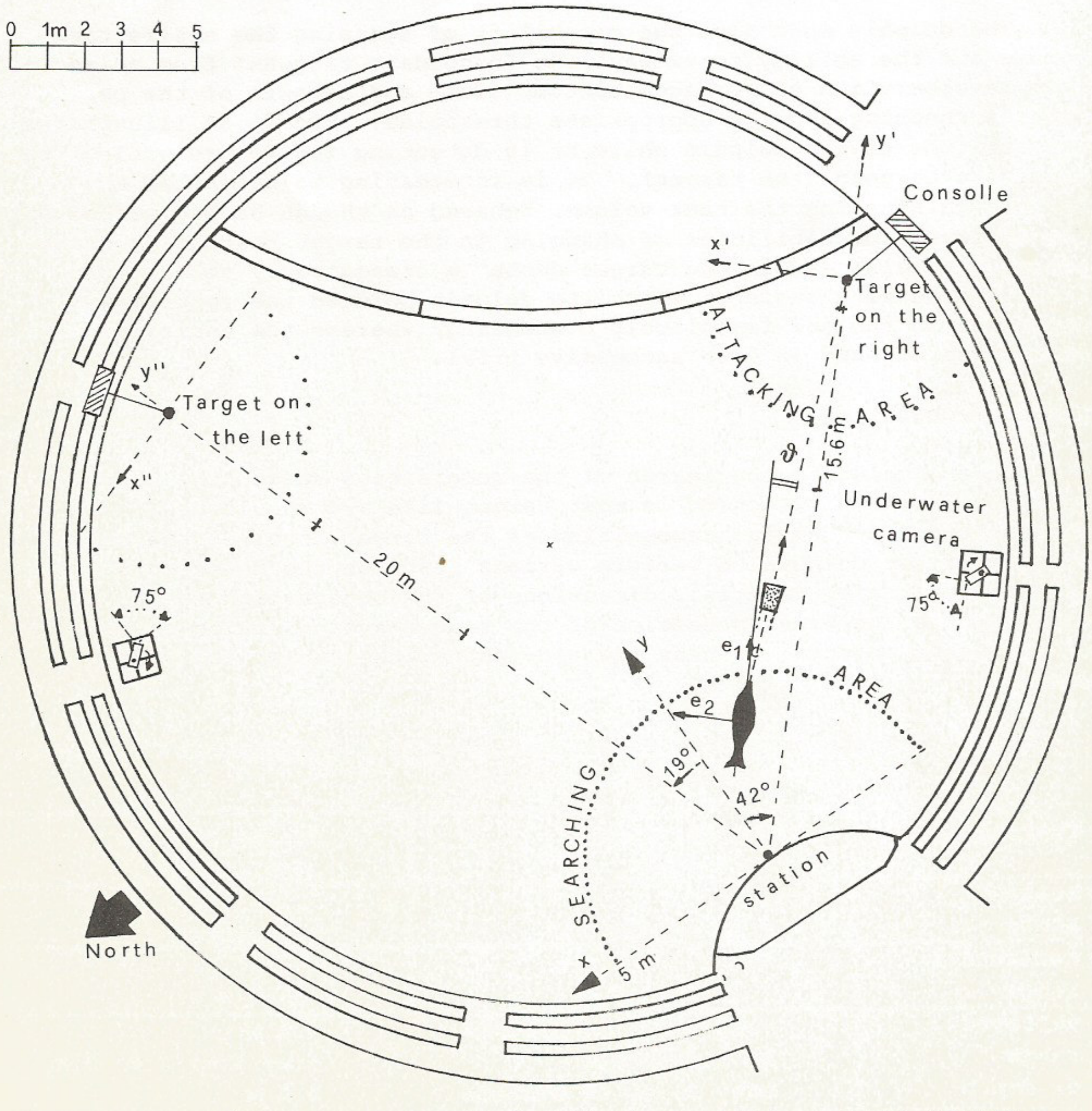

Fig. 2. Experimental set-up showing the two position of the target.

$$\underline{R}^b (t_0) = R (t_0) \cdot \underline{p} (t_0)$$

where:

R (t) is the magnitude of the distance between the rostrum and the target

$\underline{p}$ (t) is the unit pointing vector; it measures the bearing θ and the azimuth ψ angular displacement of the rostrum, referred to the three primary axes of the dolphin body (e_1, e_2, e_3):

$$\underline{p} (t) = \cos\theta * \cos\psi * \underline{e}_1 + \cos\psi * \sin\theta * \underline{e}_2 + \sin\psi * \underline{e}_3$$

The dynamic echolocation (i.e. echolocation closely tied to locomotion) requires that the dolphin is able to sense non only R (t), through his sonar as in the static echolocation, but also the position, rotation and movement of his own body and head (i.e. the unit pointing vector $\underline{p}$ (t)) through the vestibular canals and the appropriate proprioceptors located in the muscles, joints and tendons. All these cues, integrated by the brain, allow the dolphin to make inference on his body position referred to the target position and to the enviroment, at the time of the target location.

SECOND PHASE: THE TRACKING PROCESS

Once target location has occurred, the dolphin begins to transduce acoustic information in tracking decisions so as to guide its own body (the controlled system) to the target. This task is performed through a sequence of target echolocations, each being accomplished through a series of decisions (body movements, rotations of head) similar in that each is intended to minimize some functions of the perceived error ($\underline{R}$ (t) vector).

A characteristic of the tracking is that the dolphin can program and reprogram his "computations", while the tracking process is in progress. This programming is a consequence of decisions which depend on the tracking-displays characteristics in the dolphin's brain and on the adaptative characteristics of the dolphin. In general, tracking-displays can be categorized as:

<u>Compensatory as in the Figure 6</u>

The dolphin "sees'' only the magnitude of the difference $\underline{R}$ (t) between the system output $\underline{S}$ (t) and input $\underline{T}$. He has no way of determining the actual position of his own body/rostrum and of the

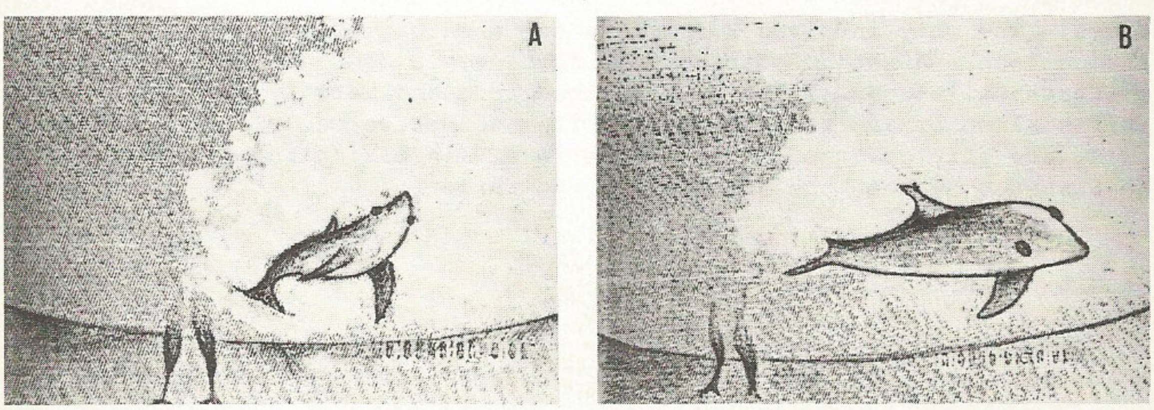

Fig. 3. (A) a typical attitude of Candy while she is detecting (and/or selecting) the "candidate targets" (the target). The other two dolphins, facing away the target in front of the trainer, are visible. (B) the dolphin locates the target (photo taken 2 seconds later than photo (A)).

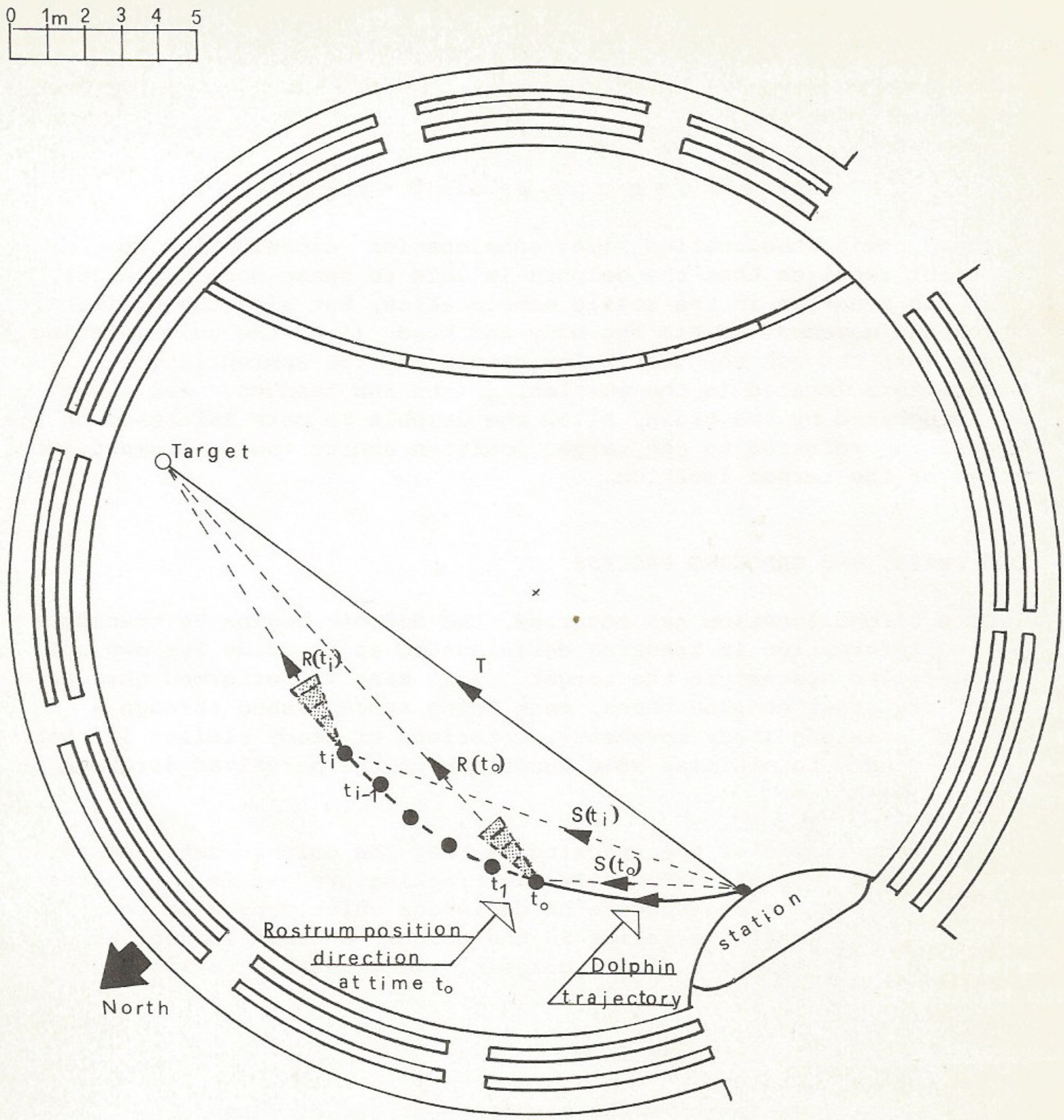

Fig. 4. A dolphin path described by the function: $\underline{R}$ (t)=$\underline{T}$-$\underline{S}$ (t). The pointing vector $\underline{R}$ (t) is perceived by the dolphin as the "error" that must be minimized to reach the target.

target. The only involved sense in a compensatory tracking is echolocation. A method of tracking, that uses a compensatory display is the Track-While-Scan (T.W.S.), described here and largely used in artificial sonar and radar systems. The successive decisions in the T.W.S. are only governed by the criteria of minimizing the magnitude of the distance between the tracker and the target.

Pursuit as in Figure 7

The dolphin "sees" his own body together with rostrum position vector and the target position vector, both as a part of an environment within which the task is to be performed. It is evident that a pursuit tracking needs additional sensing of information outside the echolocation. The tracking methods, that use a pursuit display as the triangulation method described here, are characterized by significant changes of the criteria-error-function, in accord with particular situations and adaptations. The experiment indicated different types of

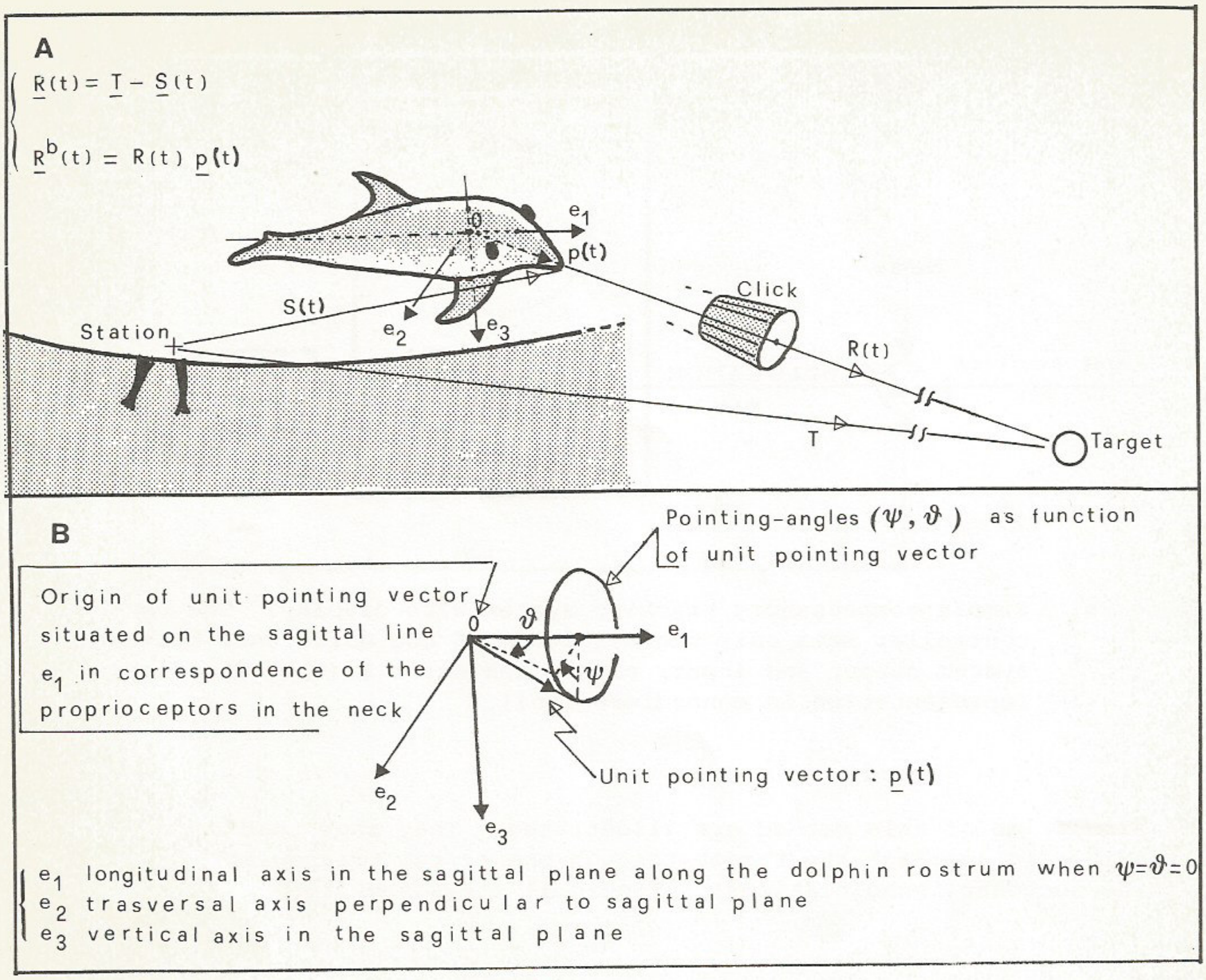

Fig. 5. (A) the pointing vector (or "error") formulated in a fixed coordinate system $\underline{R}$ (t) and in the dolphin body coordinate system $\underline{R}^b$ (t). (B) the unit pointing vector.

adaptation in the dolphin (such as adaptation to the target characteristics, to changes in procedures) and a capacity of developing skills based on past experience (learning).

FROM T.W.S. TO TRIANGULATION

At the beginning of the experiment, the dolphin approached the target using the method called Track-While-Scan (T.W.S.). The dolphin tried to retain the target in track (adjusting the position of the body and head, the click repetition), until the range R (t) (i.e. the perceived error) went to zero. In Table 2 is summarized the T.W.S. method, very well known in sonar/radar compensatory tracking systems. The number of clicks that illuminated the target was never less than 40. In some trials the dolphin seemed to drop the track after a series of K consecutive failures to update the target (K = drop-track threshold, unknown). Then the tactical behaviour of dolphin slowly evolved until in the last experiments (February/May 1988), he adopted an unusual strategy of target approaching. The target was ensonified by a number of clicks much lower than in the first trials (two or three clicks); the approaching path was not linear, as in the first experiments, but a poligonal-like curve; in the neighbouring of the target (the attacking area) the path assumed an arc of spiral shape. Table 3 and Figure 8 suggest a mathematical explanation of this behaviour based on successive triangulation method. In Figures 9, 10 and in Tables 4, 5 the results of

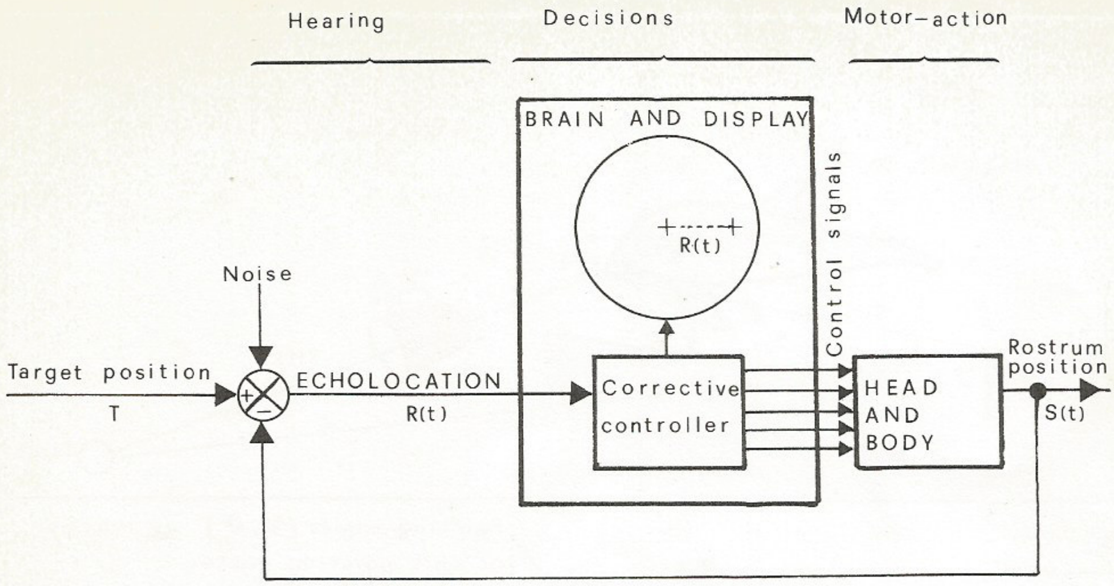

Fig. 6. Simple compensatory tracking system with display. The controller sees only the magnitude of the difference between the system output and input, namely the error R (t). The display representation is mono-dimensional.

a simulation of this method are illustrated. They show that it is possible to approach the target through one or two triangulations (two or three successul echolocations). Figure 11 shows some typical attitudes

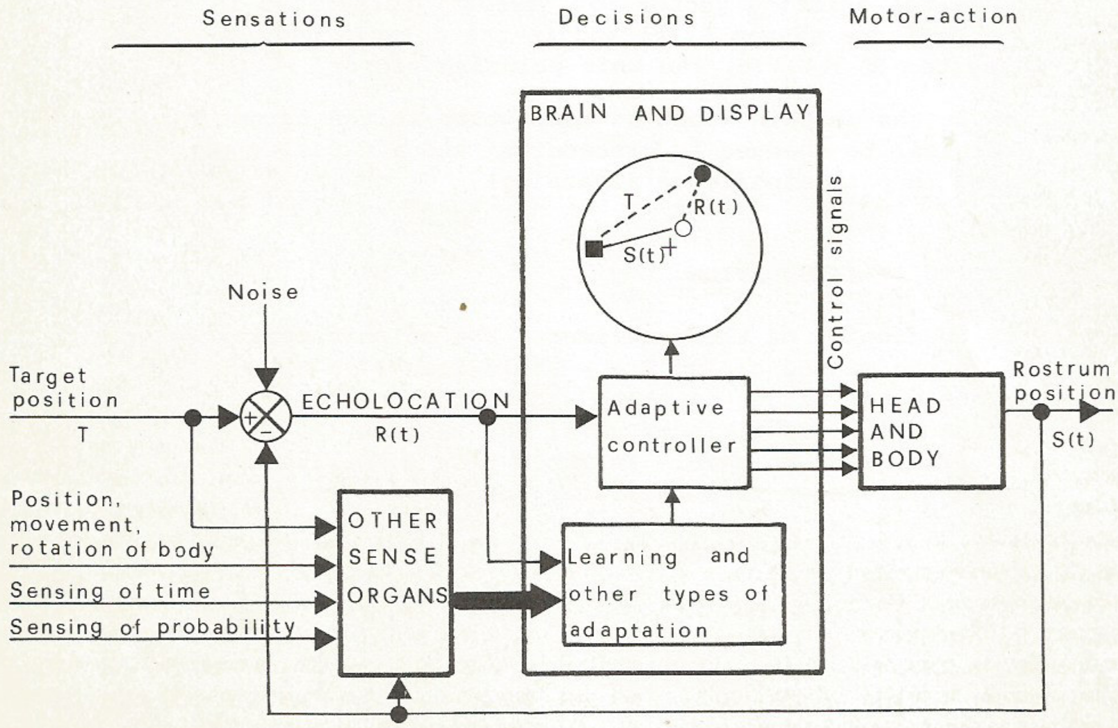

Fig. 7. Simple pursuit tracking system with display. The controller sees its own body with rostrum positions and the target positions, as well as their difference R (t). The display representation is in three-dimensional space.

Table 2. Track-While-Scan Method

a	At the time (t_0) of the first echolocation, the dolphin measures the initial range $R(t_0)$, the bearing $\theta(t_0)$ and the azimuth $\psi(t_0)$ angles.
b	Dolphin orients with the rostrum towards the target.
c	Dolphin swims along a line-like path, emitting clicks at time intervals Δt. The closing path is described by: $$\underline{P}(t)=\underline{S}(t_0)+\frac{(t-t_0)}{(t_f-t_0)}*(\underline{T}-\underline{S}(t_0))$$ where t_f is the time of impact
d	Range decrement per clicks is: $\Delta R=V*\Delta t$, so that the range $R(t_j)$, corresponding at the click j is: $R(t_j)=R(t_0)-j*V*\Delta t;\ j=1,2,\ldots N;\ V=\text{speed}$
e	Expected number of clicks emitted by the dolphin between the time of the first echolocation t_0 and the time of impact t_f is: $N=((1/\Delta t)*R(t_0))/V$ For ex. if $(1/\Delta t)\geq 10s^{-1}$; $R(t_0)=20m$; $V\leq 5m/s$; then $N\geq 40$
f	Expected number of clicks that illuminate the target is: $M=N*p(R)$; $p(R)=$ average probability of updating the target in function of range R.

of the dolphin in the tracking phase. The triangulation method assumes that:
(1) the target is "quasi-stationary"relatively to the dolphin.
(2) The dolphin has a precise perception of the position and angular movements of his body and head, viewed as a part of the environment, that includes the target. This implies the use of other sense organs in

Table 3. Triangulation Method

a*	At the time (t_0) of the first echolocation, the dolphin measures the initial range $R(t_0)$, the bearing $\theta(t_0)$ and azimuth $\psi(t_0)$ angles. The bearing is stored θ_0.
b*	The dolphin turns through a free angle $\Delta_1<\theta(t_0)$ left (right), if the measured bearing angle is left (right).
c*	The dolphin swims along a line for a distance D_1 until he echolocates again the target at the same stored bearing angle θ_0. If $R(t_1)$ is the second measured range, at the time t_1 then $$\frac{D_1}{\sin\Delta_1}=\frac{R(t_0)}{\sin\theta_0}=\frac{R(t_1)}{\sin(\theta_0-\Delta_1)}$$
d*	At the time t_1, the dolphin turns again through a free angle $\Delta_2<\theta_0$ and swims for a distance D_2, until he echolocates the target at the stored bearing angle θ_0. If $R(t_2)$ is the third measured range at the time t_2 then: $$\frac{D_2}{\sin\Delta_2}=\frac{R(t_1)}{\sin\theta_0}=\frac{R(t_2)}{\sin(\theta_0-\Delta_2)}$$
e*	The dolphin, arrived in an area around the target, attacks it using a large variety of strategies.

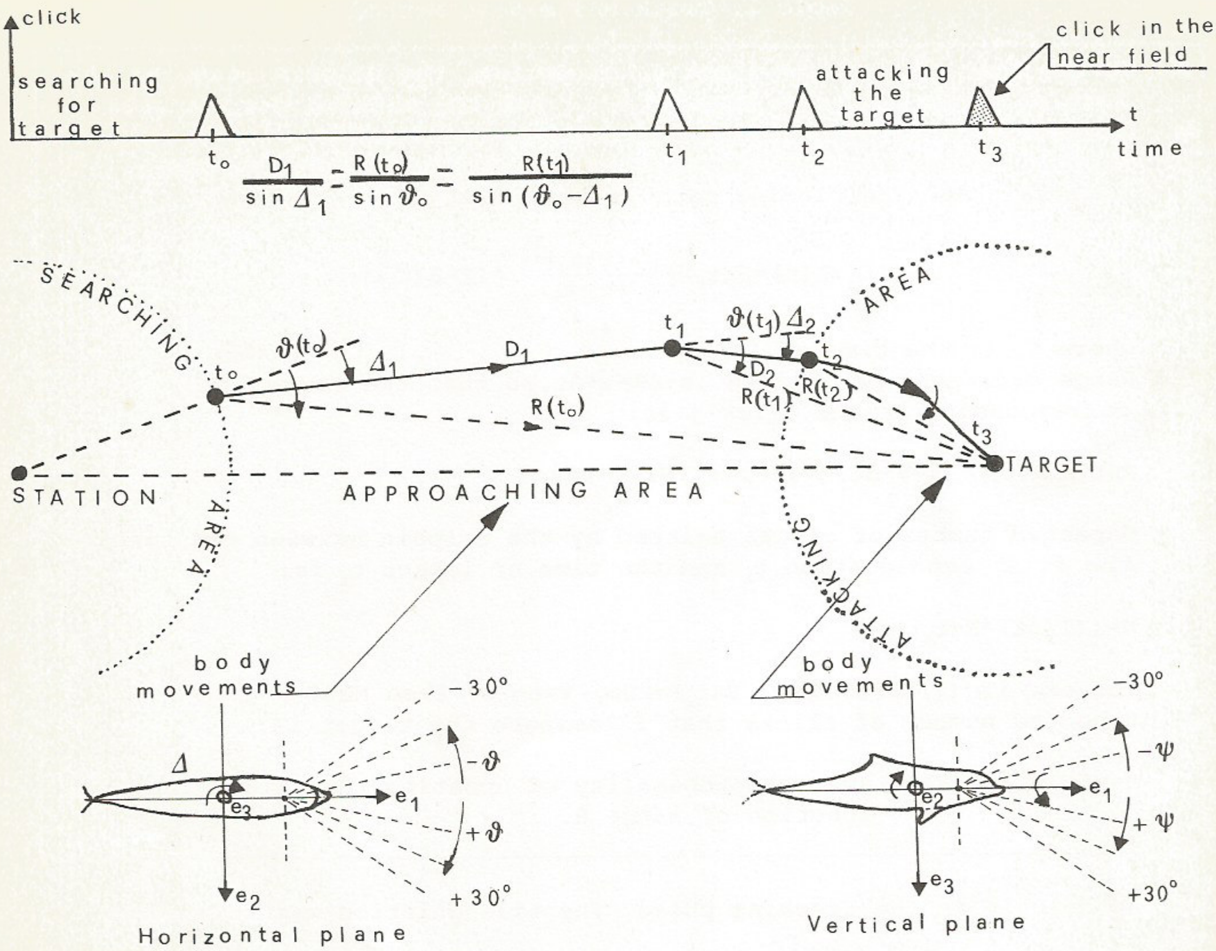

Fig. 8. Operational illustration of the triangulation method (Table 3 describes the relative algorithm). The triangulation is a "precognitive" method of tracking. The dolphin, choosing freely the turn angle Δ_i, can guess the future distance to be travelled (D_{i+1}) and the future range ($R(t_{i+1})$).

addition to echolocation.
(3) The dolphin has a versatile and complex mental display mechanism (pursuit tracking display). It allows the dolphin to have a "his body position image" that includes the target as well as the environment (see Figure 7).

The triangulation method needs a brain activity higher than the T.W.S. method, but offers many advantages.
(a) It is less sensitive to errors and it is stable. Therefore, the drop-track events are less frequent.
(b) The dolphin can program and reprogram the trajectory of approaching the target, while the tracking process is in progress.
(c) The triangulation method, differently from T.W.S. method, guides the dolphin smoothly to an area around the target, from where the dolphin can attack the target using a large variety of strategies.

ATTACKING STRATEGIES-THIRD PHASE

Arrived in the attacking area, the dolphin changes his tactical behaviour. He moves and rotates the body along spiral-like trajectories. Figures 12 and 13 illustrate typical behaviors of the dolphin, attacking the target. The trajectories depend strongly on the depth of the target and on the rostrum-to-target vector at the moment of last echolocation.

Table 4. Summary of Dolphin Orientation During Triangulation (see Fig. 9)

Number of triangulation	2 triangulations on the right			2 triangulations on the left			2 triangulations on the right		
Time (t_i) of echolocation	t_0	t_1	t_2	t_0	t_1	t_2	t_0	t_1	t_2
$R(t_i)$ in m	17.0	10.4	4.3	16.0	10.7	2.4	15.5	7.4	3.5
$\theta(t_i)$ in deg.	25	25		15	15		28	28	
Δ_i in deg.	10	15		5	10		15	15	
D_i in m	7.0	6.3		5.4	7.2		9.5	4.1	
Remarks	The dolphin arrives in the attack area with 2 triangulations (3 echolocations)								

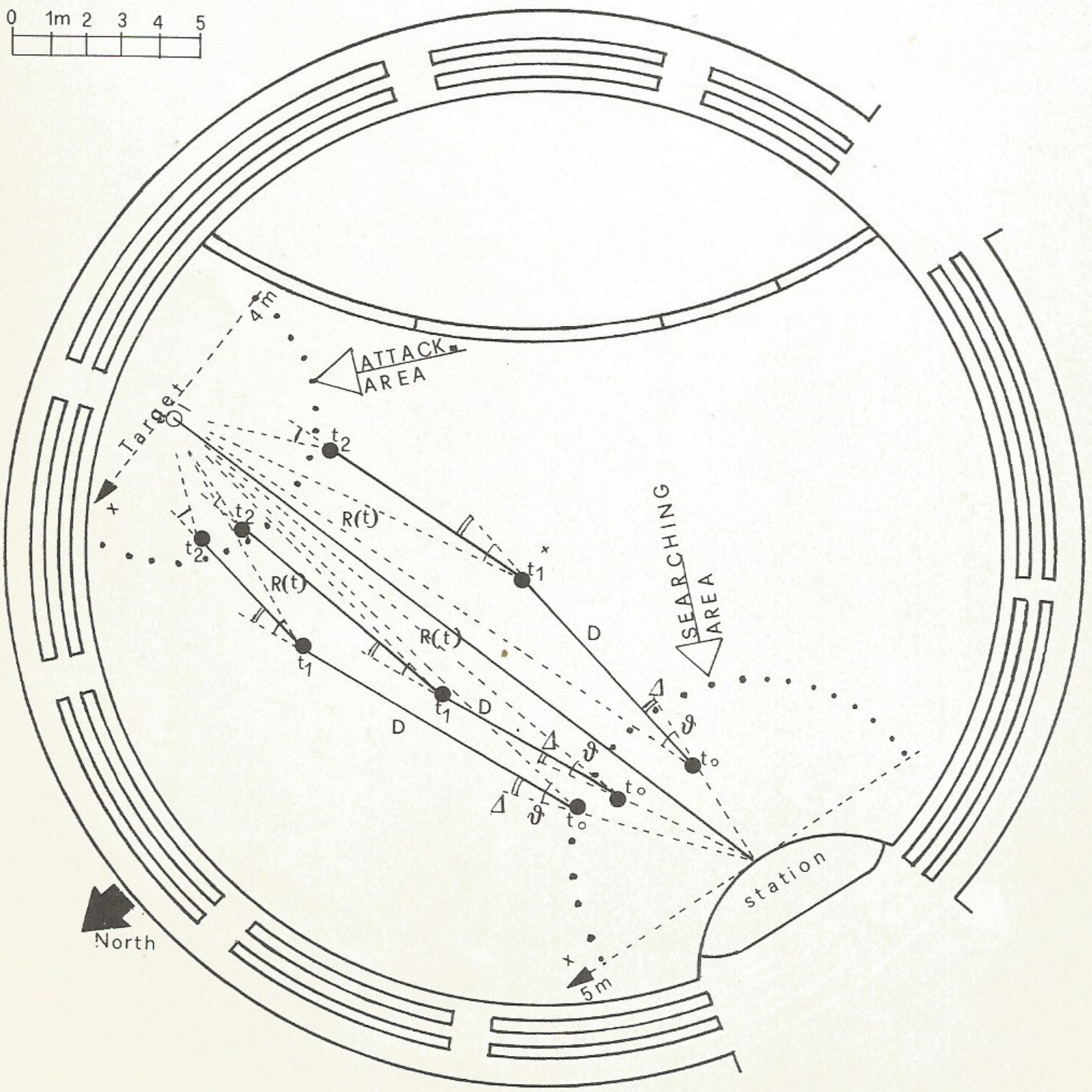

Fig. 9. Results of a simulation of the "triangulation method" (target on the left). They show that in general 2 triangulations are necessary to approach the target (confirmed by trials).

Table 5. Summary of Dolphin Orientation During Triangulation (see Fig. 10)

Number of triangulation	2 triangulations on the right			1 triangulations on the left		2 triangulations on the right		
Time (t_i) of echolocation	t_0	t_1	t_2	t_0	t_1	t_0	t_1	t_2
$R(t_i)$ in m	12.5	6.4	3.3	11.7	4.4	11	5.9	3.1
$\theta(t_i)$ in deg.	20	20		16		31	31	
Δ_i in deg.	10	10		10		15	15	
D_i in m	6.3	3.2		7.4		5.5	2.9	
Remarks	The dolphin arrives in the attack area with 2 or 1 triangulations (3 or 2 echolocations)							

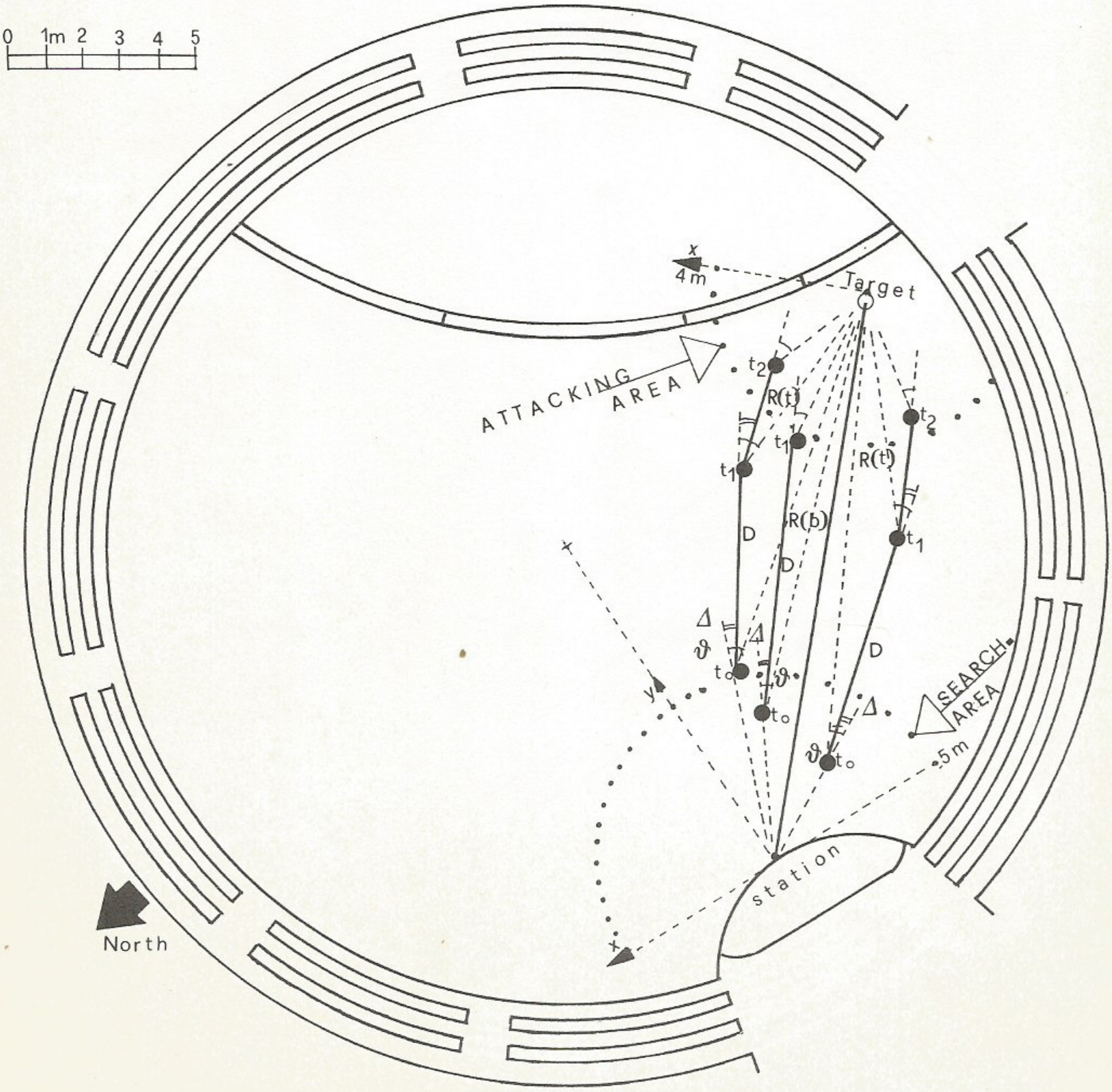

Fig. 10. Results of a simulation of the triangulation method (target on the right). They show that sometimes it is possible to approach the target through 1 triangulation (confirmed by trials).

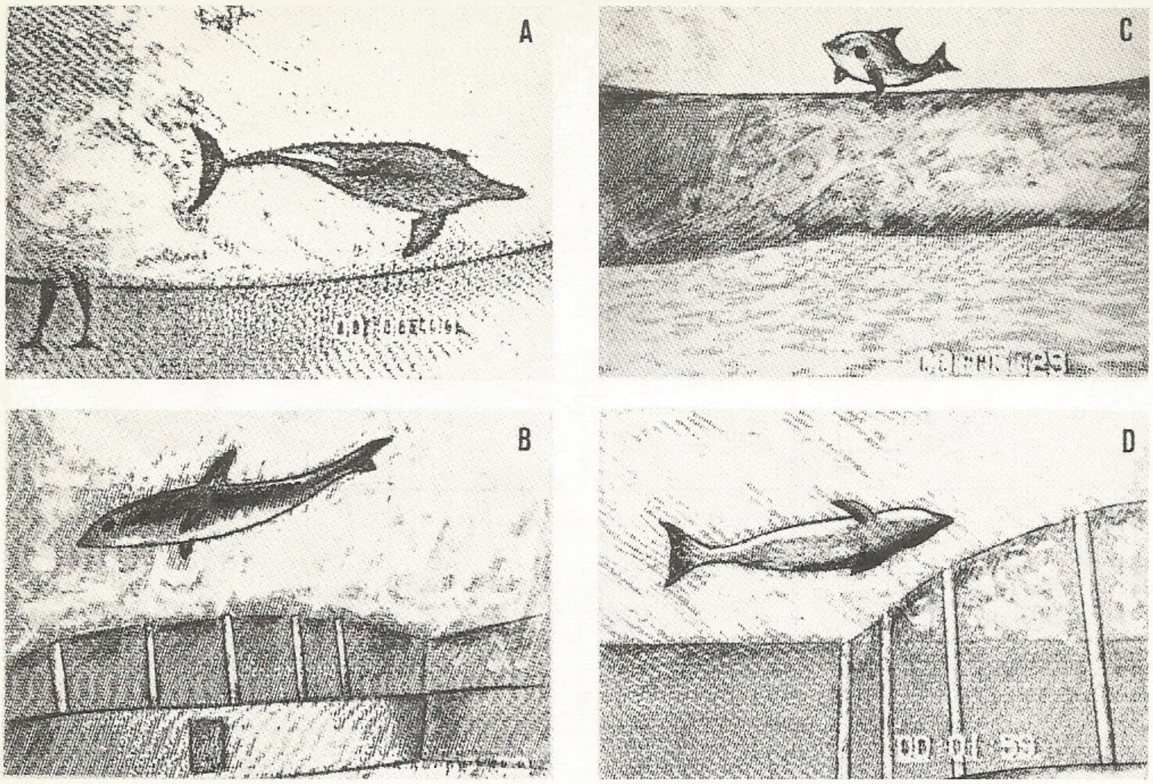

Fig. 11. Typical attitudes of the dolphin in the tracking phase. A, B: the target is on the left; C, D: the target is on the right.

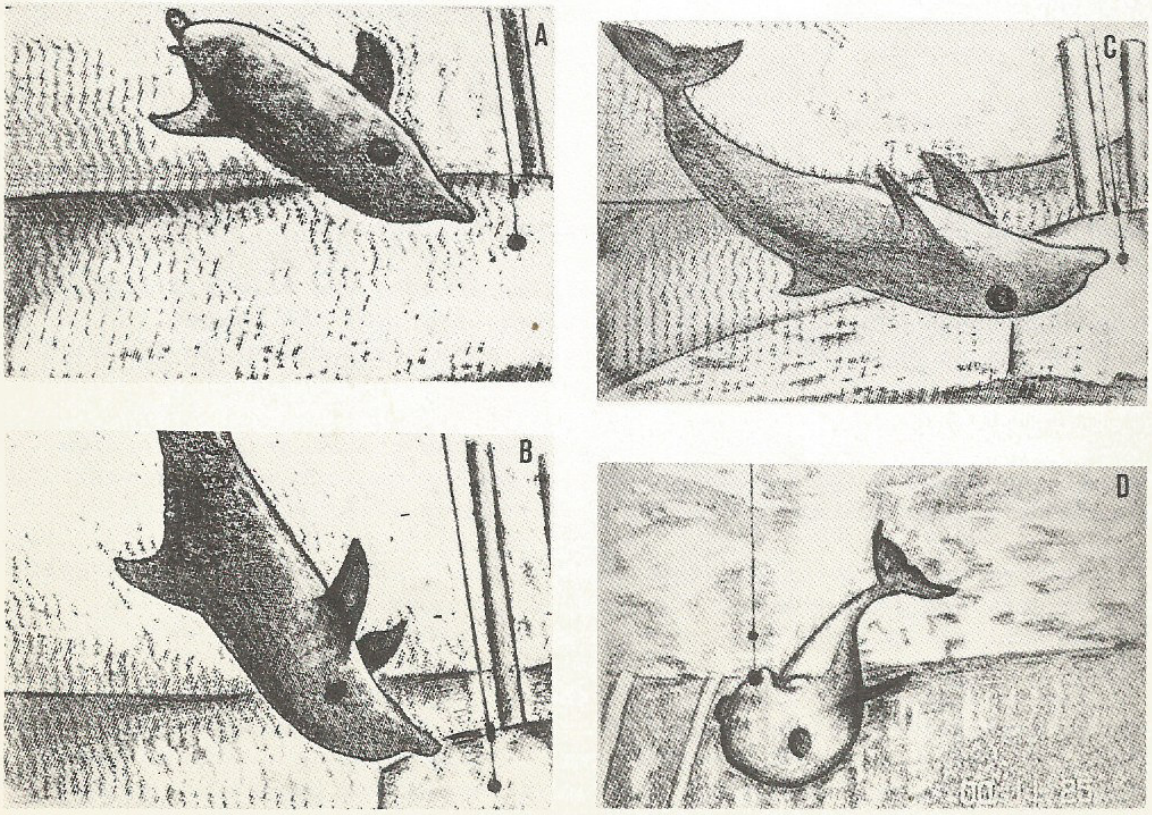

Fig. 12. The photos illustrate some typical attitudes of the dolphin in the final phase of tracking, when he echolocates the target in the near field.

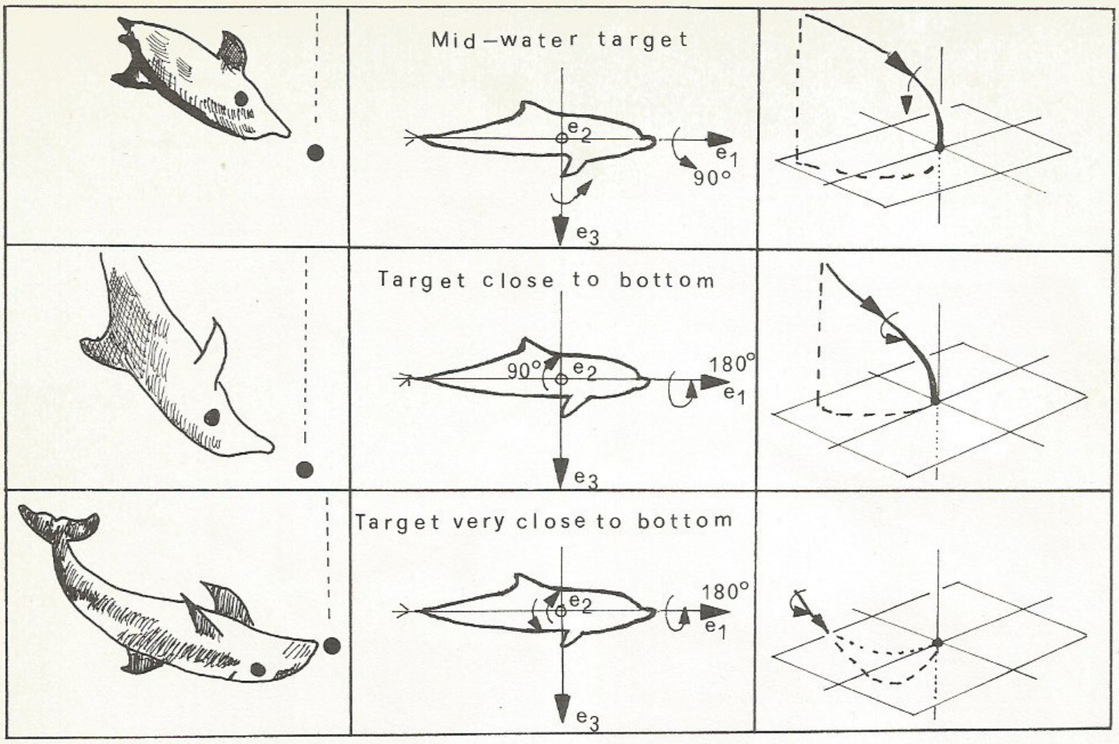

Fig. 13. Schematic representation of the dolphin attacking the target, in three tipical situations. If the target is in mid-water, the dolphin attacks it from up-to-down, rotating the body up to 90° around e_1 axis. If the target is close to bottom, the dolphin attacks it yet from up-to-down but rotating the body up to 180° around e_1 axis and up to 90° around e_3 axis. If the target is very close to bottom, the dolphin prefers to attack it from down-to-up, with the body completely reversed.

Roughly one can distinguish three basic situations.

Target close to surface. The dolphin attacks the target slightly from down-to-up. The dolphin, when arrives very near the target, echolocates it just before making contact with its rostrum (in the near field).

Mid-water target. The dolphin attacks the target from up-to-down, travelling along a spiral curve. Before making contact with its rostrum, the dolphin echolocates the target (see Figures 12 A, B and 13).

Target very close to bottom. The dolphin makes a nose-dive against the target, rotating the body so that he can echolocate and hit the target with the rostrum from down-to-up (see Figures 12 C, D and 13).

It is interesting to note that the dolphin always echolocates the target immediately before making contact with its rostrum and this last click, in the near-field, has structural characteristics very different from the clicks emitted in the far-field, during the phases of searching and approaching the target.

CONCLUSIONS

The study, based on 72 trials, focuses on the tactical behaviour of a blind-folded dolphin that searches, locates, approaches and attacks the target. The dolphin improved his tactical behaviour performances during the experiment. In the training period and in the first trials he seemed to concentrate on the "error" as it is displayed in a T.W.S. (or compensatory) tracking system. Then the dolphin seemed to become capable of making appropriate inference on the position, rotation of his own body/head and on the position and acoustic characteristics of the target. He used these cues and, probably, some stored information, to approach the target in a very unusual way. It seemed that the dolphin was tracking "precognitively" and acting as a "pursuit tracking system". It is tried to interpretate those results assuming that the dolphin after having learned the task, is able to approach the target using successive triangulations. This method offers many advantages respect to the T.W.S. method.

The hypothesis suggested here requires further verification and, if confirmed, opens many problems as:
(1) are the acoustical strategies related to single individuals and/or to individual temporary dispositions?
(2) How much do characteristics of the environment/the captivity condition affect the tactical behaviour of a dolphin?
(3) How will the dolphin react to a moving (or live) target?

AKNOWLEDGMENTS

The participation of the Adriatic Sea World in the Research National Council program has provided the circumstances for developing the work. In particular, the authors would like to thank Dott. Cariglia G. and Dott. Stanziani L. of the A.S.W., who trained the dolphins and have been very helpful in many ways, Valsecchi E., student of Pavia University, and Dott. Tangerini P. for their assistance in the experiments.

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