EL SONAR BIOLÓGICO DEL CACHALOTE: DETECCIÓN DE OBJETOS POCO REFLECTANTES

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Resumen - **La contaminación acústica en el medio marino constituye un problema emergente. Sus implicaciones para el equilibrio de los ecosistemas marinos no son tan evidentes como otras amenazas globales y pueden incluso pasar desapercibidas para el no especialista. Además, el asesoramiento del impacto acústico producido por fuentes artificiales en el mar no es una tarea trivial, en gran parte porque existe una carencia de información y datos objetivos sobre cómo los organismos marinos perciben y analizan los sonidos y se desconoce la relevancia de estas señales acústicas en términos de desarrollo de las poblaciones. Este posible impacto acústico concierne no solamente las vías de recepción acústica pero también otros niveles sensoriales y puede resultar dañino e incluso letal para los animales expuestos. Si se añade que las consecuencias de una exposición a una fuente sonora artificial pueden que no se observen a medio plazo, se entiende que la obtención de datos objetivos para asesorar y controlar la introducción de ruido antropogénico en el mar constituya en la actualidad un reto científico. Para contestar a algunas de estas preguntas, la elección de investigar a los cetáceos y sus adaptaciones al medio acuático no es casual. Los cetáceos, porque utilizan los sonidos como fuente de energía y porque dependen casi exclusivamente de su producción y recepción para desarrollar sus actividades diarias representan no solamente los mejores bio-indicadores de los efectos de la contaminación acústica marina pero también una fuente de datos para mejorar y desarrollar las tecnologías acústicas marinas. Presentamos como las características del sonar biológico del cachalote pueden ser de interés para desarrollar soluciones de mitigación basadas en acústica pasiva e imagen por ruido ambiente para prevenir las interacciones con actividades humanas y monitorizar los movimientos de cetáceos en áreas de interés.**

The Sperm Whale mid-range sonar: detecting low reflective objects

***Abstract* - Noise pollution in the marine environment is an emerging but serious concern. Its implications are less well understood than other global threats and largely undetectable to everyone but the specialist. In addition, the assessment of the acoustic impact of artificial sounds in the sea is not a trivial task, certainly because there is a lack of information on how the marine organisms process and analyze sounds and how relevant these sounds are for the balance and development of the populations. Further, this possible acoustic impact not only concerns the hearing systems but may also affect other sensory or systemic levels and result equally lethal for the animal concerned. If we add that the negative consequences of a short or long term exposure to artificial sounds may not be immediately observed one can understood how challenging it is to obtain objective data allowing an efficient control of the introduction of anthropogenic sound in the sea. To answer some of these questions, the choice to investigate cetaceans and their adaptation to an aquatic environment is not fortuitous. Cetaceans, because of their optimum use of sound as an ad-hoc source of energy and their almost exclusive dependence on acoustic information, represent not only the best bio-indicator of the effects of noise pollution in the marine environment, but also a source of data to improve and develop human underwater acoustic technology. Here, we present how the characteristics and performance of the sperm whale mid-range biosonar can be used to develop a mitigation solution based on passive acoustics and ambient noise imaging to prevent negative interactions with human activities by monitoring cetacean movements in areas of interest.**

I. INTRODUCTION

Sperm whales are known to spend most of their time foraging and feeding on squids at depths of several hundreds of meters where the light is scarce [1]. While foraging, sperm whales produce a series of acoustic signals called usual clicks. The coincidence of the continuous production of usual clicks together with the associated feeding behaviour has lead authors to suppose that those specific signals could be involved in the process of detecting preys. Because of the usual click known acoustic signal features (e.g. source level, bandwidth and directivity index) differing from most of the described echolocation signals of other species, it has been long speculated about the sperm whale sonar capabilities. While the usual clicks of this species were considered to support mid-range echolocation, no physical characteristics of the signal had until very recently, clearly confirmed this assumption nor have explained how sperm whales forage on low sound reflective bodies like squids. The recent data on sperm whale on-axis recordings have shed some light on those questions and allowed us to perform simulations in controlled environments to verify the possible mid-range sonar function of usual clicks during foraging processes and assess the threshold of cetacean tolerance before noise pollution in the ocean.

II. SCATTERING AND TARGET STRENGTH

A. Sperm whale acoustics

On-axis sperm whale clicks are broadband (ranging from 0,2-30kHz), highly directional (DI = 26dB), last for a few ms and present a SL of 230 dB $_{peak}$ re 1microPa [12]. Clicks recorded off the axis of the beam pattern present a much lower directivity index and are several orders of magnitude weaker than the main on-axis pulse. The on-axis clicks have an average centroid frequency of 15 kHz. Möhl and colleagues [8]) and more recently Zimmer and colleagues [12] have constructed the beam pattern of the components of a sperm whale click, P0, P1, P2 and so on as well as a LF component, each of them having its own characteristics although generated by the same acoustics event. While P1 would serve an echolocation function, the LF and P0 components would be used for dive synchronisation between members as well as long range orientation. Due to its high directionality, the forward-directed P1 pulse is well suited for echolocation. The high source level of the P1 pulse and the long ICI of usual clicks suggest a potential for long detection ranges.

B. Scattering off reflective objects

What is the scattering mechanism occurring off a squid when illuminated by an on-axis sperm whale click and what would be its minimum distance of detection?

The type of scattering that occurs off a reflective object is governed by the ratio of a representative length of the object and the wavelength. This is quantified by the product *ka*, where *k* is called the wave number (2Pi divided by the wavelength) and *a* represents the length of the object. Assuming the sound speed in the water is around 1500m/s *ka* can be expressed by: 4 x f[kHz] x a [m].

If *ka* >> 1, a geometric scattering applies where the frequency dependence of the target is weak: In that case the target strength of fish, squid, crab can be approximated only from the knowledge of the body length of the animal to within an error of 6dB.

If *ka* <<1, the Rayleigh scattering occurs. Here the target strength increases linearly with frequency and depends little on the particular scatterer.

At *ka* close to 1 there is a transition region where the TS can change dramatically with frequency. The specific changes depend on the particular scattering object. This transition region occurs at hundreds of Hz to a few kHz frequencies for squids of the sizes typically found in the sperm whale diet. Those frequency components constitute the lower end of the sperm whale click frequency spectrum and it could be speculated that using this lower frequency end the whale is able to detect the transition region and estimate the size of the insonified object. If this was the case, the sperm whale would adopt an opportunistic feeding strategy, detecting the size of the target before any other characteristic. Such foraging behaviour has been reported to be common, especially in males.

Although it is difficult to accurately assess the typical size of sperm whale preys, most caught squids have mantle lengths between 0.2-0.7m [2,3]. Since the on-axis click occupies frequencies above 5kHz, *ka*>>1, geometric scattering usually applies. This property, i.e. the frequency independence of the target will be used further to experimentally measure the squid target strength.

C. Squid Target Strength in the literature.

There are few and fragmentary measurements of the target strength pattern for live squid [6].

Love [7] compiled measurements of fish (both with and without swim bladder) target strengths and devised two simple relations for predicting the TS from the wavelength and the animal length:

TS [dB] = 19.4 $\log_{10}$ L [m] + 0.6 ? [m] – 21.9 (dorsal aspect)

TS [dB] = 22.8 $\log_{10}$ L [m] – 2.8 ? [m] – 22.9 (side aspect)

Several authors have also measured the TS of small squids, fish and shrimps at different frequencies and these measurements have shown to fit Love's relations relatively well [4,5]. Love's relations were used to predict the target strengths of sperm whale preys at click frequencies: the predicted TS ranges (from side to dorsal aspects) at 15 kHz for squids of mantle lengths from 20-200cm. The relations predict TS values ranging from -39 to -17 dB (Fig.1).

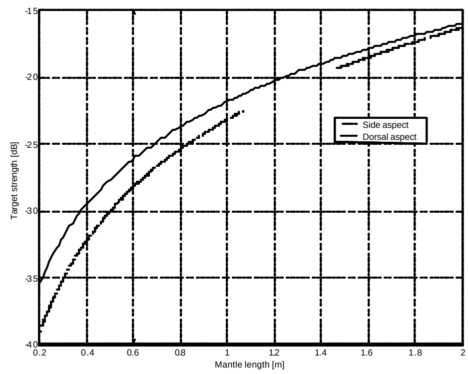


Fig.1. Predicted TS values for squids of mantle lengths from 20-200cm.

D. Squid TS measurement: experimental approach

In order to further investigate whether the target strength predictions of Love are valid for squid, and in order to see whether very weak target echoes could be accurately measured with a simple setup and simple means, we conducted measurements of the target strengths of a squid (*Loligo vulgaris*) and a cuttlefish (*Sepia officinalis*). Measurements were conducted in a 4-by-8 meter freshwater pool. The depth of the pool varied from 1.2 to 2 meters, but the measurements were done in the deep end of the pool only. The measurements were done at 15 kHz, described at the P1 pulse centroid frequency of the on-axis click. Here, geometric scattering applies (frequency independence of the target) and measurements of squid target strength could be carried out at only one frequency.

The same laptop handled both the signal generation and caption, avoiding this way timing problems. A B&K power amplifier type 2713 provided 40 dB gain on the output signal before sent to the B&K type 8104 transducer. The squid echo was captured by a B&K type 8101 hydrophone and amplified by a custom-made low noise preamplifier with a variable gain setting before being recorded.

The setup, as seen from above (Fig.2), was designed to ensure that no other echo or reflection would arrive at the receiver at the same time as the target echo and that the source waveform was short enough so the direct path signal would not overlap with the target echo.

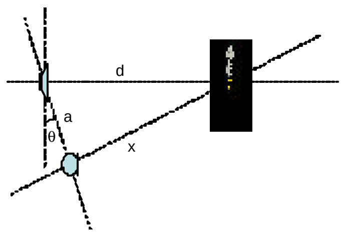


Fig.2. Measurement setup: d = 50 cm, a = 12 cm, q = 15°
x = 48.3 cm (x2 = d2+a2-2adcos(90°-q) = d2+a2-2adsinq)

We took the greatest possible care in positioning of the measurement equipment and target, and believe that the distances given here are accurate. With these distances and a pulse duration of 0.5 ms, a sound speed of 1500 m/s, and a minimum distance to another reflecting interface (the bottom) of 80 cm, the echo arrival times could be estimated as follows:

Direct path: Start at 0.080 ms and end at 0.580 ms.
Target echo: Start at 0.656 ms and end at 1.116 ms.
Other echoes: Start later than 1.067 ms.

The direct path pulse and the target echo would not overlap, but the last approximately 0.1 ms of the target echo might overlap with other reflections. In order to be sure of analysing only the target echo, we restricted the analysis to 0.7 to 1.0 ms after the pulse transmission.

A calibration measurement was conducted without any target present in the pool and with the hydrophone 1 m away from the transducer. The source level of the transducer was 90.2 dB re 1 µPa/V. There is a tolerance on this value, and its effect on the measurements will be discussed in the next section. The amplitude of the generated signal at the laptop was 1 V and the power amplifier added 40 dB, so the source level was 130.2 dB re 1 ?Pa. In linear units, this is 3.24 Pa. The pre-amplifier was set to 40 dB. Hence, the signal amplitude at the hydrophone was 0.38 mV. *This means that the transduction ratio of our system was 3.24 Pa / 0.38 mV = 8.53 kPa /V.*

The transducer was set to send out a 0.5 ms burst of a 15 kHz sine wave every 100 ms. The sine wave was ramped up and down during the first 0.1 ms with a half-sine window. The transmitted burst is shown in Figure 3, as well as its spectrum. The bandwidth of the spectrum around 15 kHz is estimated at 4 kHz between the half power points. This spreading occurs because the pulse is so short – the shorter the pulse the wider must necessarily be its spectrum.

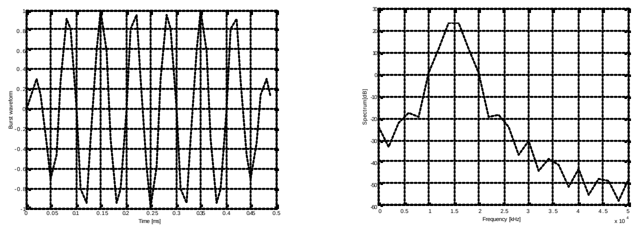


Fig.3. Transmitted burst and waveform spectrum (logarithmic scale, arbitrary reference)

Measurements were taken without a target, with the squid target, and with the cuttlefish target.

The received waveforms, converted into acoustic pressure, are shown. The pre-amplifier settings were 30, 40 and 50 dB, respectively, and this was taken into account when estimating the received pressures.

As figure 4 shows, there is a clear gap in the response between the direct pulse and the first reflection from the surface or bottom. The target echo occurs just in this gap: while the cuttlefish echo is easily discernable, the squid is harder to see.

Zooming in on the squid signal between 0.7 and 1.0 ms shows that the signal clearly changes when introducing the squid target (Fig.5). There waveforms were obtained by averaging 5000 returns.

The differences are greatest at 0.75-0.8 ms and 0.85-0.95 ms. The greatest peak-to-peak amplitude of the squid echo is 0.41 Pa. and 1.16 Pa. for the cuttlefish.

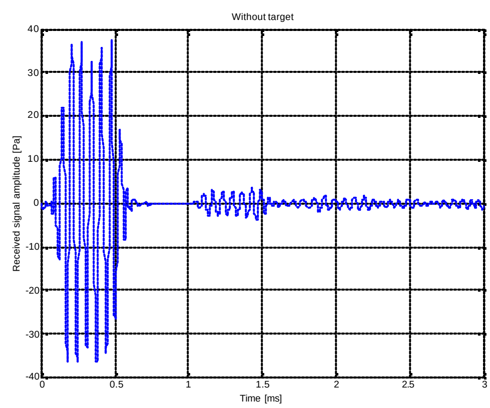


Fig. 4. Received waveform converted to pressure, no target present

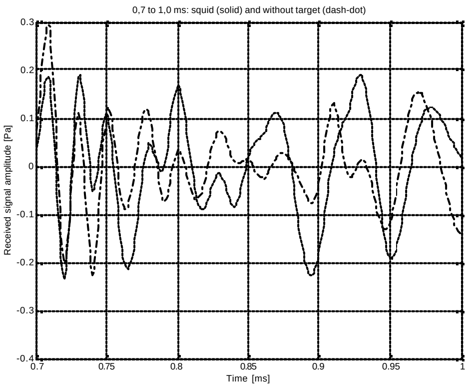


Fig.5. Received sound pressures from 0.7 to 1.0 ms lags without a target (dash-dot) and with a squid target (solid).

F. Target strength estimation

The target strength of a scattering object is defined as

$$TS = 10 \log I_r/I_i = 20 \log p_r/p_i$$

where I_r = the acoustic intensity of the scattered sound at a distance of 1 m and I_i = the incident acoustic energy

Same correspondence for the pressures p_r and p_i. The illuminating source should be distant, so that the illuminating sound wave is plane. Here, the source was 50 cm away, which at 15 kHz corresponds to 3.3 wavelengths. $kd = 20 >>1$, corresponding to a far field configuration. The source is also sufficiently small that the wavefront is approximately plane over the extent of the target.

We measured the pressure of the scattered sound field at a distance *x* from the scatterer. Therefore,

$$P_r = P_{measured} * x$$

We have previously calculated the sound pressure of the incident field at 1 m distance as 3.24 Pa. Here, we need the pressure at a distance *d* from the source. This is simple to obtain as:

$$TS = 20 \log p_r/p_i = 20 \log p_{measured}/p_{1m} + 20 \log xd$$

Using the following parameters:
$p_{measured,\ squid}$ = 0.41 Pa / 2
$p_{measured,\ cuttlefish}$ = 1.16 Pa / 2
p_{1m} = 3.24 Pa
d = 50 cm
x = 48.3 cm

we obtained the target strength of the squid and the cuttlefish as being: TS_{squid} = -36.3 dB and $TS_{cuttlefish}$ = -27.3 dB

It is interesting to compare these values to what would be predicted from Love's general relations for scattering in the geometric scattering region (which applies here). The one for dorsal aspect reflection is:

TS [dB] = 19.4 $\log_{10}$ L [m] + 0.6 ? [m] – 21.9

The squid, with a mantle length of 21.8 – 24.5 cm (ventral - dorsal), is predicted to have a target strength at 15 kHz of between -33.7 and -34.7 dB. This agrees well with our measured value, especially considering the tolerances detailed below.

For the cuttlefish, with a mantle length of 13.4 – 15.6 cm (ventral - dorsal), the predicted TS is between -38.8 and -37.5 dB. Although the measured value is more than 10 dB greater, this discrepancy cannot be blamed on the measurement tolerances. Instead it appears likely that the cuttlefish reflects far more acoustic energy than many other sea animals of the same size because of its cuttlebone, which is very light and thus likely to have very different acoustic impedance to water. This probably causes the greater reflection than that which occurs off, for example, a squid.

The transducer tolerance of 2.5 dB translates to the same tolerance on the TS. This leads to ranges of

TS_{squid} = -36.3 ± 2.5 dB = -38.8 to -33.8 dB
$TS_{cuttlefish}$ = = -27.3 ± 2.5 dB = -29.8 to -24.8 dB

III. PROPAGATION

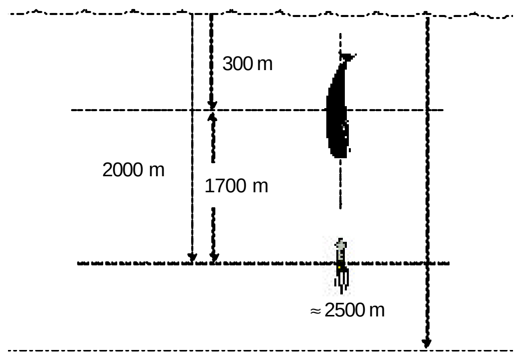
A. Modelling the sperm whale click propagation vs squid TS

Different numerical techniques for estimating the propagation of acoustic energy in the ocean were considered [9,10]. It was found that at frequencies above a few kHz, ray tracing was the best option. Seeing that it is the least computationally intensive of the available methods, it would also be desirable to use it at lower frequencies. This might be possible if all dimensions in the environment are much smaller than the wavelength. However no detailed verification was performed.

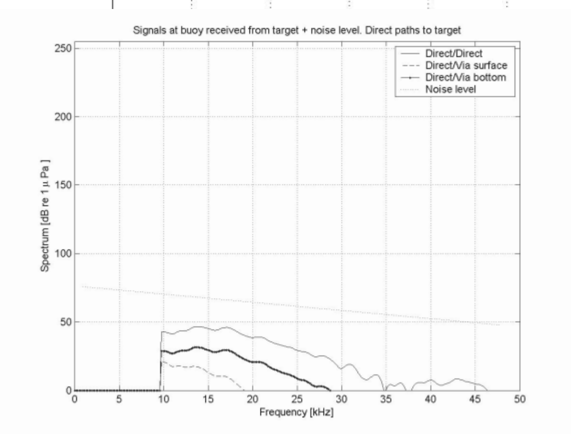
Normal mode modelling and wavenumber integration were also found to be suitable for the application, although the computational requirements of these models at 15 kHz and in typical sperm whale environments appeared, at least at present to prevent their use.

Parabolic equation models suffer from the same high frequency problem, and are also only suitable for propagation near the horizontal plane.

The LAB has developed a ray tracing software called Songlines. This software runs broadband propagation modelling in three dimensions with target reflections. A scenario with a vertically diving sperm whale at a depth of 300 m and a squid at 2000 m depth was developed in the model. The depth at the modelling location was 2495 m. All propagation was vertical and along straight rays. This permitted a simple modelling which still allowed us to draw important conclusions.



The sperm whale click source level of 230 dB_{peak} and the diameter of the modelled circular piston radiator of 0.8 m, as given by Mohl et al [8] were used. The *Loligo vulgaris* specimen with a target strength of -36.3 dB used for the measurements was also used as the imagined target in these simulations. The



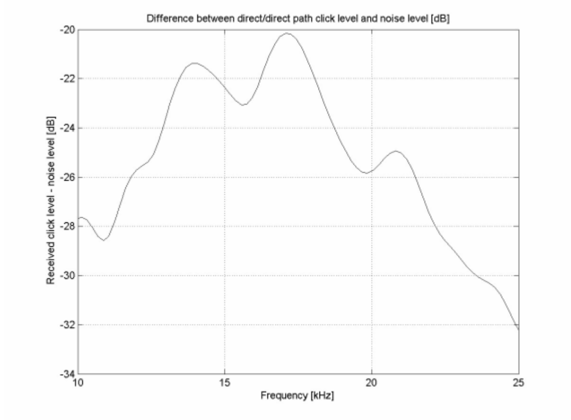


Fig. 7. Difference between direct/direct paths received click spectrum and noise level, Songlines squid run

The simulation results showed (Fig.6) that in order for the spectrum level of the direct/direct path target echo to be the same as a typical deep sea noise level at sea state 1 (a reasonable RMS noise level in the RMS bandwidth of the on-axis click is 70 dB re 1 µPa [11]), the sperm whale would need a hearing directivity of between 21 and 24 dB between 13 and 18 kHz.

Hearing directivities of 21 dB have been measured for dolphins, so such values do not appear unreasonable. This implies that it seems likely that the sperm whale could detect a single small squid of around 25cm long at a range of 1.7 km against a sea state 1 noise background. Higher sea states would require a more directional hearing or a better signal processing by the sperm whale auditory system. Directional hearing would also be helpful in attenuating the returns from surface and bottom reverberations. The effects of reverberation from non-specular scattering at the sea surface and seabed were not included in the simulations.

B. Noise Pollution

In light of recent mortality events, it is becoming clear that man-made noise, at different intensity levels, can affect negatively cetacean populations, including displacement, avoidance reactions, collisions with ships, mass stranding and death. Evidence is particularly strong that high intensity active sonar, and other loud noise sources, like those from shipping, gas exploration, seismic surveys, etc., cause lesions in acoustic organs which are severe enough to be lethal. The same sources may also produce behaviours that cause acute lesions which eventually lead the animals to strand and die. The current scientific knowledge on the effect on noise on marine mammals and their habitat is insufficient to understand the relationships of frequencies, intensities, and duration of exposures in producing damage.

To determine whether an animal is subject to hearing loss from a particular sound requires understanding how its auditory system interacts with that sound. Basically, if one can hear a noise, at some level it can damage hearing by causing decreased sensitivity. Major research efforts have to be directed at understanding the relationships of frequencies, intensities, and duration of exposures in producing damage. In other words, which sounds, at which levels, for how long, and how often will produce temporary versus permanent hearing loss.

Based on the results of this study, we now have some basic element to start to answer some of these questions, since masking could be one of the primary effects of noise pollution on the cetacean sonar capabilities.

C. Mitigation solutions

All cetacean species are prone to collisions with fast vessels, but in specific areas of high cetacean density the Sperm Whale (*Physeter macrocephalus*) is of highest concern. Sperm Whales are highly vocal and hence can be localized with passive sonar. However, when at or near the surface, they tend to stop vocalizing, *i.e.* when they are most at risk. Ship-borne active solutions have proven inefficient due to the short detection range and the ship high-speeds. A passive bistatic sonar solution, which uses vocalizing whales at depth as the acoustic sources and detects their reflections from silent whales can be developed. A simulation tool for 3D acoustic propagation was designed where a wideband 3D curved ray solution of the wave equation is implemented. This tool was developed to simulate a bi-static solution formed of an arbitrary number of active acoustic sources, an illuminated object, and a receiver all positioned in 3D space with arbitrary bathymetry. The software recreates the resulting sound mixture of direct, reverberated and echoed signals arriving at the array sensors for any array configuration and any number of sources. One object can be placed in the water column and its impact on the acoustic field at the receiver is resolved. The software simulations set bounds as for the concept viability. Detection and bearing estimates could be evaluated for silent whales at ranges of 1500m from a 4m diameter array of 32 hydrophones, where on-axis click source and ambient noise levels were respectively set to 230dB*peak* re 1µPa @1m (full bandwidth) and 60 dB*rms* re 1µPa in the 1-10kHz band.

IV. CONCLUSION

TS experiments on small squids at 15kHz confirmed theoretical measurements and gave values of around – 36 dB for squid with a mantle length of 25cm.

The sperm whale on-axis click would allow to detect a single 0.2m squid at a range of 0.9 to 1.7km depending on sea state noise levels, with a reasonable directional hearing. Large aggregation of squids would extend this range and allow the detection at several km

Sperm whale usual clicks appear to be suited for a mid-range echolocation on very low reflective and relatively small organisms like squids (< 1m).

These results confirm the necessity of defining and quantifying the added average power spectrum and spatio-temporal variability of acoustic pollution from different sources and the resulting changes in the marine environment to assess their effect on biological sonar.

Acknowledgments

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