The song of air and water: Acoustic experiments with an Ecuadorian Whistle Bottle (c.900 BC–100 BC)

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Cite this as: Ayala, M. A. *et al*. 2019 The song of air and water: Acoustic experiments with an Ecuadorian Whistle Bottle (c.900 BC–100 BC), Internet Archaeology 52. https://doi.org/10.11141/ia.52.2

Summary

In Ecuador, bottles as containers for liquids appeared in the Late Formative period at the end of the Machalilla culture (1600 BC to 800 BC). Whistle bottles were created and perfected during the Chorrera culture (900 BC to 100 BC), and finally evolved into polyphonic bottles during the Bahía culture (500 BC to 650 AD). During the Chorrera phase, moulded aesthetic elements were developed and incorporated:, such as zoomorphs and anthropomorphs, phytomorphs, architectural forms, whose animated references were related to the acoustics they produced, giving 'onomatopoeic' sounds of nature (e.g. birds, monkeys, frogs). The current research focused on the structural and systematic study of a double ellipsoid ornithomorph bottle with a whistle from the Chorrera-Bahía culture (900 BC to 100 BC), an object that is currently in the National Archaeological Reserve of the Ministry of Culture in the city of Quito, Republic of Ecuador (Ch-B-1-38-69) (Figure 1). Two replicas and the original were investigated *in situ* by the Universidad Central del Ecuador and it was possible to determine that both blowing into and moving the objects when filled with water produced the sound. We

interpret this as a need to 'automate' the sound production, and the acoustics derived from the movement of water is what possibly motivated Crespo (1966) to call them 'magical objects'.

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- Keywords: Ecuador, Chorrera culture, ancestral acoustics, whistle bottle, sounds by hydraulic action, video, audio
- Look out for: the video and the audio files
- This research was carried out in the laboratories of the Faculty of Arts of the Central University of Ecuador. The publication was financed with the researchers' own resources supplemented by the Open Access Archaeology Fund. To both institutions we offer our thanks.

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1. Introduction

Humanity in the course of its cultural development has left some testimony of its acoustic skill, evidenced in the sound-producing objects found across diverse contexts throughout history. On the Pacific coast of the Republic of Ecuador, the creation and development of one such acoustic device is the whistle bottle, locally known as "botella silbato" (Crespo 1966; de Espinoza 2006; Estrada *et al*. 1962; Ontaneda 2007) which has been attributed to the Chorrera culture (900 BC to 100 BC).

Chorrera culture occupied the area of the Ecuadorian coast from the province of Esmeraldas in the north, to the valley of Jubones in the province of El Oro to the south, achieving its greatest development along the central coast of the province of Manabí. In addition, it spread to the provinces of Cañar and Azuay. Evidence of this culture has also been found in Santo Domingo de los Colorados (Estrada *et al*. 1962).

Because the development and distribution of the Chorrera culture originated within the territory of the Republic of Ecuador, Estrada *et al*. (1962) catalogue it as a distinctly Ecuadorian culture. However, for de Espinoza (2006) the culture not only extended over large geographic territories within the country, but also, for many centuries, influenced the technical and artistic development of distant peoples in places such as Mesoamerica, Peru and Argentina.

The culture advanced economically based on agriculture, the result of its privileged geographical location on the shores of the sea or of large rivers such as the Daule and Babahoyo, which facilitated both fishing and the development of agriculture. With basic needs met, this allowed time to venture into other activities identifying a more settled lifestyle and the availability of leisure, such as stone and shell carving, textiles and working ceramics with great technical and artistic capabilities (Crespo Toral 1966; Ortiz 1981; de Espinoza 2006). The Chorrera culture is outstanding in its ceramic craft practice, an activity that demanded the careful selection of materials, technical knowledge, manual skills and aesthetic qualities to manipulate and explore the clay's potential.

Scott (1998) has corroborated the contributions of Meggers and Evans (1957) regarding the existence of an influential Chorrera style on the Ecuadorian coast, the same one that spread into the north of Ecuador and south-west Colombia. This style was characterised by the representations of naturalistic figures with monumental, serene, bulky features, with striking colours. Citing Estrada, Scott (1998) recognises as outstanding the type of heads called Solid Matte and Hollow Matte within the Final Chorrera period. He concludes that the key decorative features of the ceramic Chorrera style were incised, iridescent paint, red paint in sections or with black in incised areas. As for the shape of the objects, these could be bowls with ring base, whistle bottles with vertical slope and flat handle, 'spittoons', napkin ring earmuffs, and Hollow Matte figures and solid naturalists (Scott 1998). Additionally, the moulded anthropomorphic statuettes (Cummins 2003) can be seen as figurative sculptures and not as figures to be destroyed in rituals like those at Valdivia (Ontaneda 2007). For more recent definitions of the Chorrera Culture and its relationship with the northern Andes, see Zeidler (2008).

For Gartelmann (2006, 168), the art of the pre-Columbian cultures of Ecuador seems to have been heavily laden with a symbolic meaning without implying that many of the works were created only with exclusive artistic intention. This can be evidenced in the Chorrera style embodied in ceramic objects. However, he considers that a greater development was the representation of symbolic religious, magical, social and even economic meaning (Gartelmann 2006, 168). Certain works of art were used, for example, to appease ancestors and gods, ensure good harvests, cure the sick or as a symbol of unity of clans and peoples (Gartelmann 2006, 168). According to Klumpp (2017, 4), the potters of the Ecuadorian coast began to manufacture ceramics with technique and artistic excellence unparalleled in the pre-Columbian record of this region. Some of these fine ceramics, intended for ceremonial use, were decorated using an almost transparent paint, whose color had a metallic reflection of silver or red. This is the so-called iridescent paint, which is often found on bowls, plates and whistle bottles. The designs of this painting are composed of bands and dots, which generally are the width of a fingertip. In summary, it can be assumed that for the Chorrera potter, the transformation of specularite into paint and its use to create iridescent designs, was a spiritual and sacred activity, which was charged with symbols rooted in the principles of an Andean cosmology.

All this suggests that the selection and transformation of the ceramic materials via colourants were charged with a symbolism based on their Andean cosmovision. In the specific case of the whistle bottle, apart from the aesthetic and utilitarian function of storing and transporting liquids, some authors attribute ceremonial functions for their 'magical concept' (Crespo 1966). For other researchers, like Acosta (1974), the vessel representing water is a source of life-giving and it stands out in the myths and art of ancient America as a symbolic vessel, an inexhaustible provider of food, because it contains the fluid from which everything came (Acosta 1974, 35). For Gartelmann (2006) it is evidence of a possible musical sensibilty and an attachment to nature. Stat (in Gartelmann 2006) suggests that people are sensitive to the tonal frequencies that the objects emit and react accordingly. Ontaneda (2007) emphasises the use of the whistle bottle in the cult for ritual libations of *chicha* (a corn-based drink), since it is often found in funeral offerings. Weinstein (2007) interprets the artefacts from a metaphorical viewpoint, through the cosmology of the South American myth (past and present), seeing them as gourds, representing containers that contain life and death as plants that possibly were early natural containers. These ceramic objects, "made of earth and water, transformed by fire and air" (Weinstein 2007, 325) also symbolise the maternal womb of mother earth. The absence of wear in these objects allowed Weinstein (2007) to propose that they were used as funeral offerings. All these authors are in general agreement about the spiritual relationship of these objects with funeral, ritual and festive events, and consider that they were used exclusively by priests in ceremonies, mainly of water worship.

When looking at their construction, the whistle bottles required knowledge and technical mastery of clay, espcially during the construction of the acoustic system. Because the loss of moisture of this material causes the object to contract when passing through the different states of the construction process (from wet, to rigid, to dry and finally firing), if there is no optimal moisture control in the assembly process the whistle can move in a way that would change or cancel the sound.

The representations, embodied in different bottles with multiple containers, contain one or two whistles that are part of a complex internal acoustic system, allowing the production of sound through aerodynamics and/or hydraulics (the movement of liquid). For this reason they could be regarded as objects of great technological achievement in the field of sound for that time.

Existing research on this type of object has been scarce and usually focuses on formal, functional, acoustic-structural analysis. Using the knowledge and practice of ceramics, this research aims to enhance the picture set out by Crespo in his pioneering document in which the evolution of this object is described (1966).

Based on the functional and formal characteristics of these objects, Crespo (1966) determined six evolutionary phases. In this work we analyse the external components that make up the double ellipsoid ornithomorphic bottle with a whistle of Chorrera-Bahía culture (an object belonging to phase five according to Crespo). In addition, it includes the analysis of the acoustic effect that occurs in the sound device, which is observed through the external holes located in the head of the bird.

The methodology used for the present investigation consists of the documentary and bibliographic analysis of the subject, the construction of two replicas in the ceramic laboratory of the Universidad Central del Ecuador, and the testing and recording sounds of the original bottle and the replicas, analysed in an acoustic laboratory. This allows us to demonstrate the importance of the arrangement of the components of the acoustic system and to show the different ways these objects produce sound.

2. Evolution Phases of the Whistle Bottle

According to Crespo (1966), the shape and function of the whistle bottle evolved over approximately 1500 years. For Crespo (1966, 6) the Chorrera culture, through its movements along the Ecuadorian coast, acquired and added elements such as the stirrup handle, the painted red bands, and parallel incisions on the edge of the vessels from the Machalilla culture. The stirrup handle, which improved transport of the bottle, was incorporated into the simple bottle, which already had a small hole created to make it easier to pour liquids.

According to Crespo, the whistle bottle develops and evolves in the Chorrera culture, the great culture of the Late Formative (Crespo 1966, 2), at the end of the Machalilla culture (1600 BC to 800 BC). It would be at this point in time when the whistle was incorporated in the base of the handle, taking advantage of the air coming out of the small hole. This idea for acoustic production was possibly taken from aerophones such as zoomorphic flutes, whistles and ocarinas (Idrovo Urigüen 1987). Human and animal representations were added later, and modelled with great dexterity.

Crespo (1966) states that in this phase, the double resonance box or resonator was also incorporated, which made modification of sound via perforations possible. The mainly zoomorphic sound that comes from the bottles maintains a relationship with the animals that are represented (Crespo 1966; de Espinoza 2006; Ontaneda 2007). On the other hand, de Arce (2015, 28) argues that this is unfounded in the vast majority of cases, since there are bottles with different iconographies that sound the same, or bottles with similar iconography that emit different sounds, as well as representations that can barely be related to the sound emitted.

Crespo considers that the double container bottle appeared as a 'synthesis' of the 'primitive bottle' and the whistle bottle, and which in this investigation has been called an assembly, i.e. the union of the simple bottle and the whistle bottle via the conduit and the handle. In this bottle, the sound is produced by a tilting movement enabling the water contained within the bottle to move from one container to the other via the central conduit. At the end of this evolutionary synopsis, Crespo ascribes the triple globular anthropomorphic bottle with double whistle to the Bahía culture as belonging to the period 500 BC to 650 AD.

Table 1 illustrates the different evolutionary phases of the whistle bottle. Crespo's simple bottle is in Figure 2. Phase 1 is a simple bottle with hole (Figure 3); Phase 2 adds a handle (Figure 4); Phases 3 and 4 refer to the incorporation of a small resonance box, which allow them to be called whistle bottles (Figure 5 and Figure 6). Phase 5 consists of the double globular bottle (Figure 7) and finally the process concludes in Phase 6 with the triple globular anthropomorphic bottle containing the double whistle of the Bahía Culture and producing polyphonal sound (Figure 8). In this last phase, you can see the sum of all the elements incorporated in the bottles of the previous stages, plus additional detail – the whistles are not placed on the platform next to the air duct but are suspended on the conduit, a structure that also functions as a window. de Arce (2015) argues that, in this type of bottle, having three interconnected containers multiplies the potential of possible sounds when the liquid within is circulated. The organo-acoustic structure of the anthropomorphic triple ellipsoid bottle with double whistle of the Bahía culture belonging to this last stage is currently being investigated for a forthcoming publication.

Table 1. Graph adapted from the proposal on the evolution of the whistle bottle proposed by Hernán Crespo Toral (1966) in the text Birth and evolution of the whistle bottle

Functionalism and phases of evolution of the whistle bottle						
1600-800 A.C. Machalilla Culture			**900-100 A.C. Chorrera Culture**			**500 A.C. – 650 D.C Bahía Culture**
Simple Bottle	**Bottle with hole**	**Bottle with handle**	**Whistle Bottle**	**Whistle Bottle with multiple Artistic representations and successive or sequential sounds**	**Whistle Bottle of aerodynamic and hydraulic operation**	**Triple Vase. With double whistle**
	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5 ***	**Phase 6**
						
Simple bottle to transport liquids.- Meets the function of maintaining the freshness of the content, but presents difficulty when emptying the same.	Small hole, in the upper wall of the bottle. - Allows the continuous emptying of the liquid by the pressure of the air exerted from the inside.	Half-arc handle that connects the neck with the body of the bottle with small hole. - The handle was adopted from its predecessor, the Machalilla culture. This facilitates the mobility of the bottle. The pressure of the air and the movement of the water by means of the handle cause the exit of the water by the neck producing short bursts of air through the small orifice, which were later used to produce sound.	It is incorporated into the handle "a small resonance box or whistle ... the bottle sings" (Crespo, 1966: p: 9). - Possibly similar to the whistle that had already developed in other sound instruments of the time.	Besides the functionality of the whistle, zoomorphic and anthropomorphic plastic forms are tested with different types of decorations.- A double resonator is applied and with great mastery, sounds of birds, monkeys, frogs are imitated, etc. (Crespo, 1966: p:10)	Appear the bottles with double globular bodies.- The whistle is covered by an external resonator that has perforations that modify the sound directly or by fingering from the outside of the holes.	Bottle of three globular bodies, with double whistle and with polyphonic possibilities
Photographs courtesy of: Mónica Polanco, Museo Arqueológico y de Arte Contemporáneo (MAAC) of the Ministry of Culture of Guayaquil, Reserva Arqueológica Ministry of Culture of Quito and Santiago Ortiz. • * Stage that was considered for the development of laboratory tests (5).						

3. Components and Structure of the Ornithomorph Whistle Bottle with Double Ellipsoid of the Chorrea-Bahía Culture

The original bottle on which this study is based is dark brown in colour, a result of reductive firing. Its walls range between 5.0mm to 8.0mm thick and it weighs 2110g (Figure 1).

Structurally, this bottle is formed by two symetrical ellipsoidal vessels. They are joined together by a curved cylindrical conduit that rises at the ends (*conducto*). Another element that fulfils the function of joining these vessels is the bridge handle (*asa puente*), built with a slightly curved rectangular slab. The ergonomic shape of the handle makes it easy to grip the object and facilitates the movement of the bottle when generating sound by means of a hydraulic system (Figure 9).

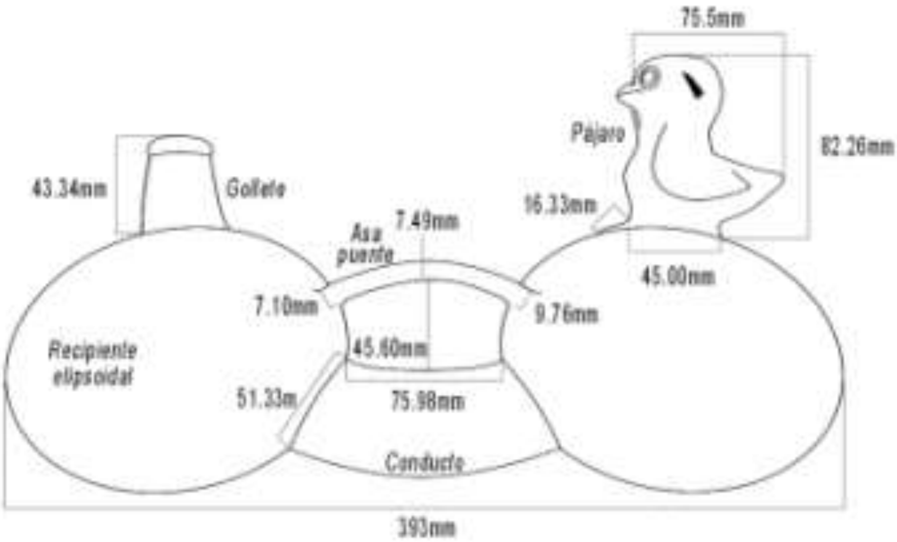
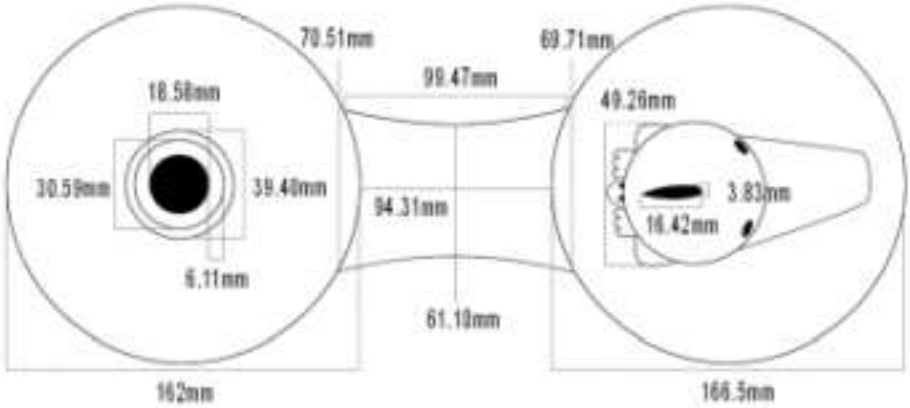


Figure 9: Side view. Drawing by Mónica Ayala 2018.

In the upper part of one of the containers the neck (*gollete*) is centred; this is cylindrical in shape with a slight decrease in diameter towards the upper part (Figure 10). Through this cylinder the liquid and/or the air enter, and is distributed through the conduit located in the lower part of the ellipsoids; elements that through blowing or tilting contribute to the sound production (Figure 11). In the neck there are traces of wear and loosening of the slip, mostly around the mouth of the vessel. This wear shows sound was possibly produced through frequent contact with the performer's mouth, a way of producing sound called direct blow; alternatively, the wear could result from introducing some liquid through the neck (Figure 12).



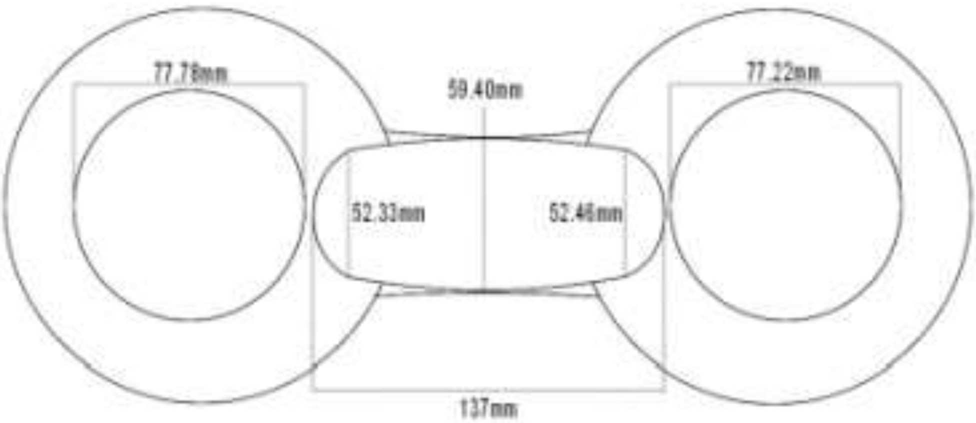
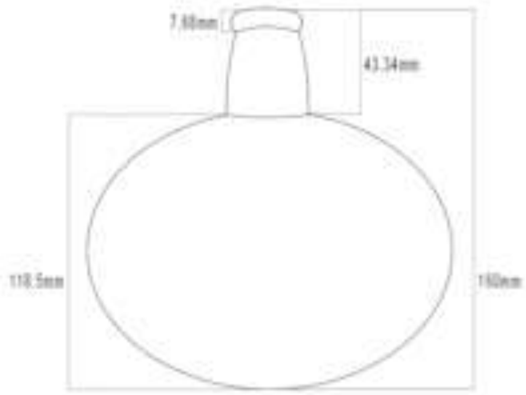


Figure 10: Top view. Drawing by Mónica Ayala 2018.
Figure 11: Bottom view. Drawing by Mónica Ayala 2018.

The ellipsoidal vessel at the other end has an ornithomorphic representation of a bird (*pájaro*) in front of the neck, with a short beak and tail (Figure 13). There are traces of iridescent paint in the form of stripes and dots on the vessel, a decorative effect characteristic of the Chorrera style as mentioned by Scott (1998). This type of painting has been studied and applied, in particular, by Klumpp (2017, 4), for whom iridescent painting is closely related, not only to the raw material used by the pre-Columbian artisan, but also to the technique used to paint. The effect is produced by using the index finger to apply an iron oxide-based paint (hematite) to the pottery body after it has been fired at low temperature.



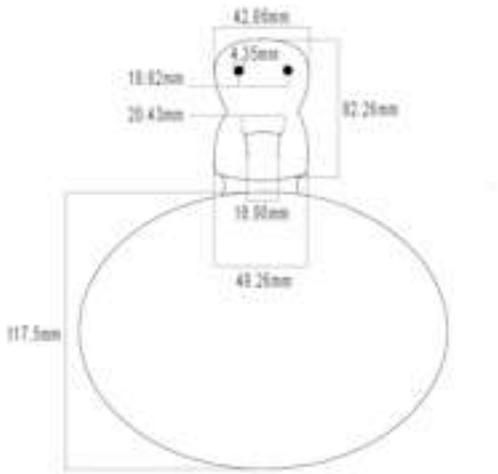


Figure 12: Neck view. Drawing by Mónica Ayala 2018.
Figure 13: Bird back view. Drawing by Mónica Ayala 2018.

On the surface of the bird, red engobe and evidence of ochre slip on the legs can be seen from the base of the neck, body and wings, a chromatic effect that also corresponds to the Chorrera style (Scott 1998). Due to the appearance of the colours and a small, almost rectangular geometric trace that is located under the bird, it can be determined that this figure was covered to prevent it from becoming contaminated by smoke at the time of reductive firing, in this way conserving the natural quality of colour of the engobe. This firing is necessary to create the effect of the iridescent paint, achieving a matte result in the bird and contrasting brightness in the ellipsoidal bodies.

In this structure of geometric components, this ornithomorphic representation is of remarkable relevance, not only because of its shape and size (70% of the height of the container that contains it) but because in it, inside the head, is hidden the whistle. The device, in this case, generates a sound similar to that of a real bird, so this becomes the most important element of the bottle.

4. Form and Dimensions

4.1 Components and structure of the acoustic system

This study has made it possible to determine that the structure of this bottle is a system designed for acoustic reproduction using aerodynamic and/or hydraulic action. It is an artefact created to generate sound through the compressed air expelled by the movement of water from inside the bottle. As a mechanism of 'high technology' for that time, it was possible to transcend the domestic function of the object. This was possible through the use of technical experience, wisdom and knowledge, which today can be explained by hydraulic and aerodynamic physical science, but which possibly were seen in the past as a spiritual need.

The acoustic system constitutes of:

a. the neck cylinder through which the air enters the vessel
b. two containers of ellipsoidal shape joined by a conduit that facilitates the passing of fluids from one container to another;
c. an air duct (*aeroducto del silbato*), a small cylindrical hole that carries air from the bottle into the whistle;
d. a whistle that is a small hollow sphere or resonator (*esfera resonadora del silbato*) with a circular hole (*orificio de entrada*) from which sound is produced (Figure 14).

The whistle is contained in the head of the bird and is by itself is a musical instrument. It is complicated to catalogue this vessel using the von Hornbostel and Sachs (1914) classification (de Arce and Gili 2013), because on the one hand it fits into the flute category (421.13) but also into the flute with duct category (421.2) (Bermúdez 1985). We accept the definition of de Arce and Gili (2013, appendix 19) and propose classifying the object as follows: 421.221.42 (indirect blow ocarina) or whistle bottle.

The acoustic device is inside the hollowed head of the bird (*envoltura externa - cavidad*), which has eight holes, as detailed in Table 2, no.6 (Figure 14).

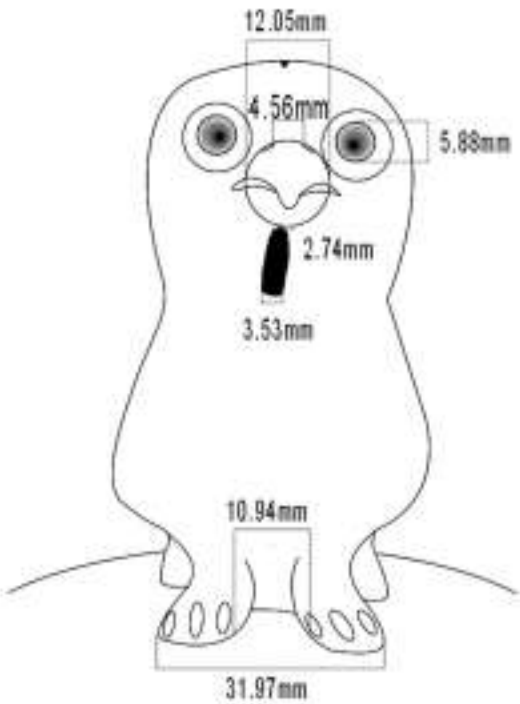


Figure 14: Structure and location of the whistle. Drawing by Mónica Ayala
Figure 15: The bird. Drawing by Mónica Ayala

4.2 Physical functioning of a flute in relation to the whistle bottle

The sound device on the whistle bottle works as follows (Figure 14):

Exciter or edge tone system: All flutes work from the same principle. Compressed air is sent through a pipe over a pointed or corner-shaped object called a labium. This phenomenon was studied by Marc Pierre Verge at the Technical University (TU) of Eindhoven (Verge 1995):

Flue instruments can be defined as acoustical systems producing sound as a result of the coupling between a hydrodynamically unstable flow and a resonant acoustic field in a pipe … The flow is generated by blowing through a narrow duct called flue. At the flue exit, a free jet is formed by flow separation. The jet flows across the mouth of the instrument and is directed towards a sharp edge called labium. Because of its intrinsic instability, the jet is very sensitive to perturbations acting on it. At the flue exit, the jet is submitted to the transverse acoustic field of the pipe. The perturbations propagate on the jet and are amplified. This results in a flipping of the jet on each side of the labium at the same frequency as that of the acoustic field … (Verge 1995, 12-13)

The resonator consists of a cavity with a certain geometry, containing air that can enter into resonance with the exciter that is physically associated with it; in part, its role is to amplify the sound. Because of its geometry the resonator enters into a feedback process with the exciter system, imposing certain tones. The resonators can have various shapes e.g. cylindrical, conical, spherical. Whistles and ocarinas are flutes because they work under these conditions.

Globular whistles are flutes and consist of a resonator, which can be spherical, oval or a more irregular shape. In the case of the whistle bottle in the current study, it has a globular whistle attached to the upper front part of the platform located in the neck of the bird. On this platform there is a perforation (air duct) that directs the air towards the hole in the spherical resonator. The edge of the entrance hole is bevelled (*bisel*) where the air oscillates (Figure 16).

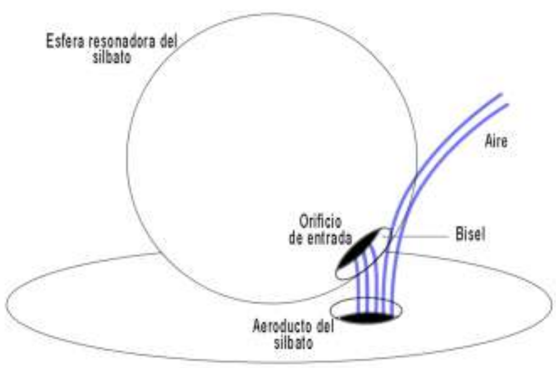


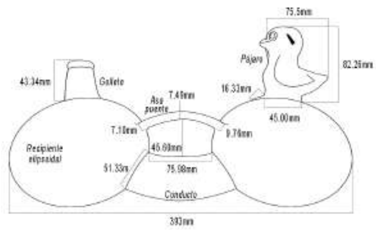
Figure 16: Exciter system of the ornithomorphic bottle. Illustration by Mónica Ayala

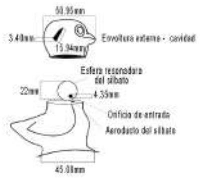
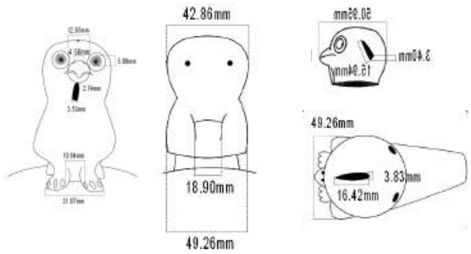
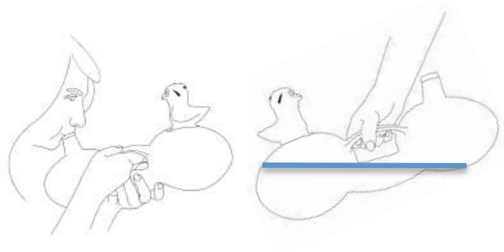
5. Laboratory Experiments

To analyse the acoustic system and the possible sounds made by the whistle bottle, laboratory experiments were carried out. The work began with the construction of a replica bottle which, after modelling, drying and firing, was 72% of the size of the original. The construction process is described in Table 2. This object would correspond to Crespo's phase 5 of the evolution of the whistle bottle.

During manufacturing, clay slabs were placed on spherical supports of synthetic material, which served as molds; similar to the technique used within ancestral practices, known as the 'false lathe' to form the vessel (Ortiz 1981).

Table 2. Process of manufacturing replica of bottle whistle in Laboratory

Double ellipsoid ornithomorphous bottle with a whistle Chorrera-Bahía culture	
1. The process started with the identification of the components and the record of measurements of the original bottle.	
2. Templates were made using a marker on a soft plastic that made it possible to take the shape of the different surfaces. The scale templates were moved to a 08.0 mm thick clay plate.	
3. Each ellipsoidal body was constructed by joining two curved plates (half spheres), previously formed on styrofoam spheres. Subsequently the other components were prepared according to the original bottle. The bird was modeled by hand and then emptied and located in the corresponding place.	
4. Once all the components were assembled in leather, an opening was made in the upper part of the ellipsoids and the neck and the bird without the head were placed very carefully.	

5. On the body of the bird, at the base of the neck, a platform was built in which a small circular hole called "airway" is made, then the whistle was integrated with great care (small hollow sphere "resonator" with a hole called "entry hole." At the time of the whistle assembly it was important to maintain the same humidity in all the components, otherwise they can be moved by the effect of the contraction and could be anular sound. Tests and acoustic recordings were made, verifying the similarity with the original.	
6. Before gluing the head to the body, details of eye and beak characterization were made; and eight holes were made in the contour of the head: 2 circular holes that make up the eyes; 2 other circular holes in the back; 2 in the form of a drop on the lateral parts; 1 also in the form of drop on top; and 1 inverted U-shape at the base of the peak. Acoustic tests and recordings were again carried out, verifying the similarity with the sound of the original bottle.	
7. Once the object was dry, it was cooked in an electric laboratory oven at 1040 degrees Celsius, because more hardness of the ceramic material is needed to carry out the multiple tests. The last acoustic tests were made by aerodynamic and hydraulic action with the respective recordings and then analyzed in the acoustic laboratory. It was verified if the application of the acoustic structure analyzed in the original bottle, made possible the detected sound variants.	

8. Replica compared to the original

Replica in comparison with the original Final result, the replica after cooking in an electric oven (1040 degrees Celsius). This bottle has an approximate proportion of 72% with respect to the original bottle.

Original bottle, open-oven cooking (reductive cooking).

Synthesis of the construction process of the double ellipsoid ornithomorphic bottle with a whistle from the Chorrera-Bahía culture. On the left replica in ceramic made by Mónica Ayala. On the right original bottle that is in the National Archaeological Reserve of the Ministry of Culture of Ecuador. Photographs made by Mónica Ayala

5.1 Laboratory results

The size of the internal resonator, as well as the diameter of the holes (air duct and resonator hole), together with the remote or near placing of the resonator in relation to the interior wall of the bird's head, constitute the formal variables that have acoustic implications. Because the quality and variety of sound depend on the combination of these variables, it is presumed that the original potters would have possessed this awareness and knowledge.

When selecting the type of whistle, the Chorrera culture potters wished to represent the sounds emitted by a bird, so to this end a resonator of approximately 15mm was used with a hole of 3mm in diameter and the 3mm diameter air duct that generated sharp sounds. This sound can vary in strength or disappear altogether if the resonator is very close to the surrounding walls of the head. Adequate space is needed for the production and diffusion of the sound through the holes in the head - the same ones used in fingering, because when they are obstructed the acoustic tones vary in some way.

A different sound is produced, but of lower intensity, when the bottle is moved with water inside and the hole in the neck is covered. The sound is similar to the chirping of some chicks. Blowing directly produces a high-pitched sound that imitates the trilling of a bird that can be modulated by closing the finger holes in the head.

5.2 Description of the acoustic phenomenon

The pierced head of the bird is the sound-emitting device, inside which is the whistle. The whistle itself is a fairly simple system. The hole of the resonator sphere is in front of the air duct and angled approximately 60°. The jet of air that comes out collides with the edge of the entrance hole of the resonator sphere and there it oscillates causing an edge tone that will come into resonance with the cavity of the sphere. This is how a whistle, a globular flute, works. However, this sound source is complicated owing to the fact that the whistle is inside a perforated cavity (the head of the bird) which reacts as an external resonator and, due to the effect of the feedback, imposes its own influence, making the system more complex with the ability to emit several sounds at once. Discussing the operation of the acoustic system, de Arce (2015, 74) considers that this remarkable function requires a very precise organology, reacting to a weak air pressure and delicate changes of dynamics, a specialization that is reflected in the construction of the bottles.

Based on the laboratory results, it was determined that the sound effect varies sequentially or successively when used in conjunction with the eight perforations in the head of the bird. This may have allowed the performer to pluralise the sound by fingering or with obstructive movements produced by the fingers near the head of the bird.

The sound in the object is produced by the jet of air that reaches the whistle. There are three possible ways to activate the acoustic system: 1) by insufflation or blowing directly, 2) by a manual action that generates the internal movement of the water within the bottle (hydraulic effect), and 3) a combination of the previous two (Video 1).

Three methods for activating the acoustic system.

In the first case, the sound is instantaneous and can vary according to the intensity with which the performer sends the air into the bottle through the neck. The air passes from the entrance chamber to the exit chamber, and leaves through the holes, creating the sound of the whistle. By blowing directly, it is possible to reach higher insufflation pressures, which imply the emission of other sounds. In addition, the musical performance (intensity and sound height) can be varied by manual action when covering and uncovering the so-called finger holes that are found in the head of the bird. These sound effects occur more easily when the object is resting on a table.

The second way to produce sound is through the hydraulic handling caused by manual movement of the bottle when it contains a certain amount of water, with movements from the handle towards the bird. This allows the liquid inside to move from one side to the other, exerting pressure on the air contained in the direction of the air duct located on the platform at the base of the neck of the bird. This air is accelerated and compressed in the duct, due to the reduction in the diameter of the outlet chamber. The air that comes out of the duct collides with the edge of the entrance hole of the resonating sphere that is aligned with it; producing one or more sounds similar to the whistling of a bird. It is an edge tone, functioning just like a flute. When the bottle is tilted back, the water returns to the first chamber, it sucks air back through the duct through the holes in the bird's head (eyes, ears, beak) and replaces the air previously expelled from the exit chamber in the first movement. This continues with each tipping motion.

The sound depends on the movement of the water; when it is directed towards the neck of the bottle or first chamber it sucks the air from the outside through the air duct (a kind of "in-breath", if we relate it to a human action). The intensity of the sound depends on the thrust of the water in motion. Another way to produce sound, also through hydraulic action, is by covering the neck of the first vessel with the thumb and making movements, thus producing a low-intensity sound similar to the whistling of birds.

In the third way of activation, the neck of the bottle is blown with water inside, which produces much longer sounds that are combined with the sounds produced by the movement of water. Modification of the sound by blocking the holes with fingers can also be used.

According to the replica laboratory tests, it is estimated that the 'best' volume of water that enters the interior of the bottle through the neck is approximately 50% of the internal capacity. More than this amount shortens the sound and the water easily spills from the duct. If it is less than 50% there is no air pressure and there is almost no sound (see Video 1).

6. Acoustic Analysis

A. Arnaud Gérard from AcústicaStudioLab de Potosí/Bolivia carried out the analysis, editing and interpretation of the samples by using the sound recordings of the two replicas and the original bottle.

6.1 Description of the measurement methodology and limitations

The ideal way to conduct acoustic studies of musical instruments is to perform sound sampling in an anechoic room in an acoustic laboratory. However, in the case of archaeological and historical musical instruments belonging to museums or collections, in general it is not possible to remove them from the museum and this is precisely the case of the example studied here. Therefore the sound samples were taken in the best possible conditions (avoiding external noises) within the environment of the National Archaeological Reserve of the Ministry of Culture, Quito. Nor could the object be tested for its hydraulic operation (with water) for obvious reasons. So the sounds were generated by direct insufflation through the neck, gradually increasing the pressure (Audio 1). The sounds were recorded using a professional digital recorder Tascam DR-40 consisting of two built-in directional microphones (20Hz-20KHz) at a standard distance of 1 metre from the sound source (whistle). The digital samples in wav 44.1KHz/16bits format were analysed and edited in the laboratory using specialised software *wavesurfer-1.8.8p4-win-i386*.

Audio 1. The four notes and decay transient from the original double chamber whistle vessel

Although the resonances in the environment in which the recordings were made could affect the level of certain components in the frequency (spectrum of partials) of the sounds analyzed, this did not appear to be important. They show a poor, almost sinusoidal behaviour (few notable harmonics) like most of the whistles, and therefore there is no option for the influence of the environment to intensify formantic areas within the main spectrum (it is quasi-sinusoidal).

6.2 Analysis of the original whistle bottle

So we proceeded in this way, blowing directly through the neck with an increasing pressure (from weak to strong) and the results continued to show the same phenomenon. Four notes are visible in the spectrogram (Figure 28) (from 1 to 4) followed by a small final sound of the decay transient (5).

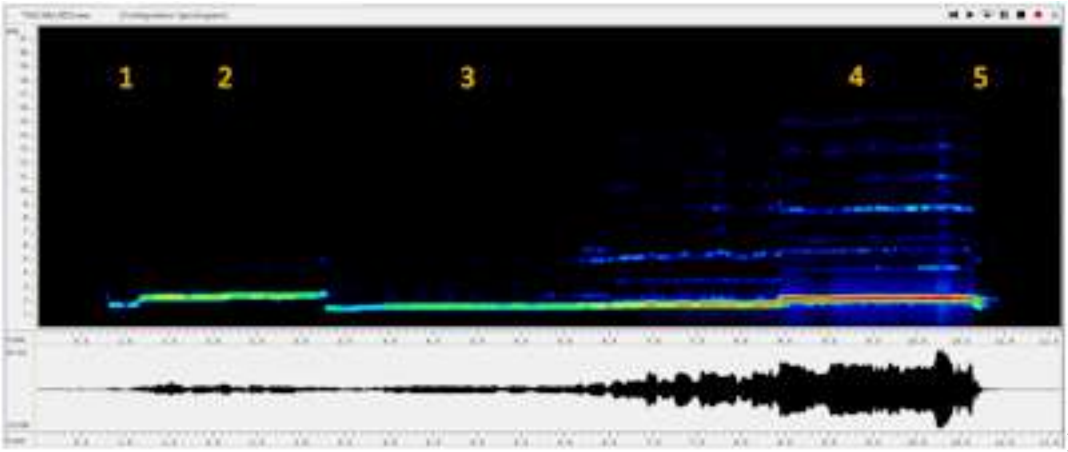


Figure 28: Above: sonogram (spectrogram); below: waveform of the sound emitted by direct insufflation into the original double chamber whistle vessel (analysis tascam_0032). Made by A. Arnaud Gérard at AcústicaStudioLab of Potosí/Bolivia, 2018.

The sonagram or spectrogram is a frequency diagram (in Hz) as a function of time (in seconds) in which the thickness of the line and the points shows the intensity (also shown in colour) of an FFT (Fast Fourier Transform) analysis (see Gérard 2011). This is a computerised algorithm that allows us to divide a sound into its different spectral components.

The spectrographic analysis can be broken down as follows (The nomenclature of the sound heights is the name of the note followed by octave (in subscript) following scientific pitch notation. The deviation in cents (100 cents = 1 semitone)):

- Stage 1: The short attack transient. A partial note is observed at 1730 Hz (average) corresponding to the note A_6-30 cents.
- Stage 2: Regime 1. The average fundamental frequency (first major component) is 2344 Hz (audible height) D_6-4 cents followed by another partial double (4810 and 4584 Hz). This sound is inharmonious. The frequency rises slightly with the blowing pressure: in fact it goes from 2273 Hz ($C\#_6$+43 cents) to 2532 Hz ($D\#_6$+30 cents)
- Stage 3: Regime 2. The average fundamental frequency is close to A_5. However, this sound is variable (field of freedom of height) and rises from 1499 Hz ($F\#_5$+22 cents) to 1775 Hz (A_5+15 cents). This dominant peak is accompanied by a peak lower than 2048 Hz followed by other partial and noise bands. This sound is also inharmonic.
- Stage 4: Regime 3. The fundamental frequency is stable near 2177 Hz (audible height) $C\#_6$-32 cents) accompanied by a minor peak at 1777 Hz followed by other partial peaks. This sound is inharmonic.
- Stage 5: Decay transient. A double peak is observed with the frequencies 1674 and 2121 Hz (height Ab_5+13 and $C\#_6$+23 cents) that are quickly extinguished.

Sequential behaviour is very atypical and anomalous for a globular whistle of this type. It repeats almost the same sequence twice (a phenomenon in all samples). The interface between the two halves occurs in 3.25 seconds.

In general, a sound is heard A_5 jumping to D_6, then goes down to A_5 (returning to the first note), then rises to a height of C#$_6$. This C# is the same partial as the note D because it can vary from C to D, as noted in the analysis of stage 2. Broadly speaking then, the A-D is heard and then the (variable) C#. This leap towards a low pitch between regimes 2 and 3 is a curious phenomenon that does not usually occur and that deserves to be studied. It would be necessary to make several models controlling the variables very precisely, which would require sophisticated equipment.

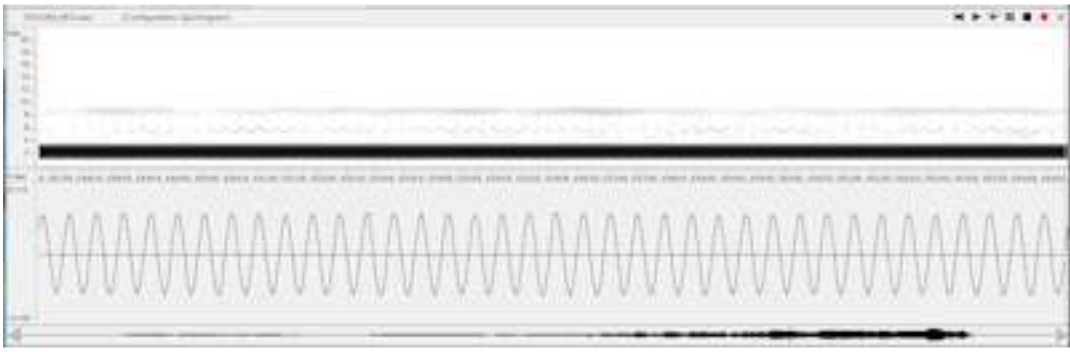


Figure 29: Oscillogram (below) of the final part (4) of the sound of the original bottle; top: a dilated sonagram in which the frequency of the first partial predominates. Made by A. Arnaud Gúrard at AcésticaStudioLab of Potosí/Bolivia, 2018.

As for the timbre, for the importance of the fundamental frequency in each case, each part of the sound has a sinusoidal tendency (almost pure tone) (Figure 29), which is the typical tone of a globular whistle or an ocarina.

In one measurement it was possible to evaluate the sound level of the whistle bottle (sensation of intensity) which reached 84 decibels at a distance of one metre, when the sound of a *rondador* (a panpipe from Ecuador) reaches 88 decibels at the same distance, meaning that the sound power is quite loud, and can be heard clearly several metres away. What the hydraulic system would have sounded like remains to be asked.

6.3 Replica tests

Sound emitted by the replica vessel through the hydraulic mechanism.

Using the scale replica, it was possible to test the sound emission through the hydraulic mechanism (Audio 2) which we argue was surely how this type of whistle bottle operated.

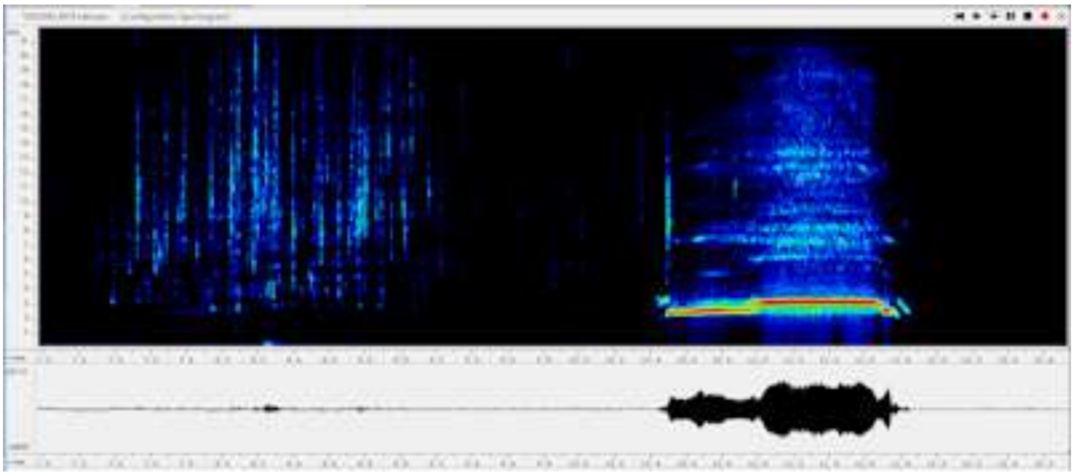


Figure 30: Above: sonagram (spectrogram); below: waveform of the sound emitted by water movement in the replica of the double ellipsoid ornithomorphic whistle bottle. On the left you can see a representation of the sound made by the clicks of the water and on the right the whistle that bears some similarity to the sound of the original vessel (analysis tascam_0079). Made by A. Arnaud Gúrard at AcésticaStudioLab of Potosí/Bolivia, 2018.

On the left of Figure 30, the sound of the air intake (admission) is demonstrated accompanied by the clicks of the water (each vertical line corresponds to a click). It looks like an inhalation next to the sound of water. The water sounds like a succession of dry high noises above 2.5 KHz. When the union pipe between the two bottles is 'uncovered', a more intense noise is produced, visible in the sonagram, similar to that produced when a bottle of cider or champagne is opened (sudden pressure equalisation). This occurs at 8.23s. On the right of the graph (Figure 30) the sound of the whistle is visualised. Four parts are shown: an edge tone that seeks accommodation with increasing frequencies ending with a sudden coupling at regime 1 (vertical line), a sound in regime 1 (horizontal line), a sound in regime 2 and a release in which the frequencies decrease rapidly. That sound has a certain similarity with the one that was observed in the original bottle, which also displayed two sound heights.

In the replica bottle, the head of the bird and the resonator sphere of the whistle are removable, which allowed a series of additional experiments to be carried out which showed important results for the research. Three tests were carried out: by placing an ultra-thin-walled plastic sphere as a whistle resonator, then changing it to a terracotta sphere with a wall thickness of 2mm and finally placing the head of the bird on top of the whistle, obtaining the following results:

- The whistle tested with the ultra-thin-walled plastic spheres only emits a single sound
- The whistle with a clay sphere with walls of c.2mm emits two sounds with or without the head of the bird. The field of freedom of height is enormous (c.500 Hz). Of note is that at higher pressure, the height of sound jumps towards a lower frequency. This is an anomalous behavior except if it were an accommodation sound of a prolonged 'attack transient'.

- Altering the head of the bird changes the spectrum of sounds: it becomes inharmonic because the cavity imposes an external acoustic field that alters the spectrum.

7. Conclusions

Based on the study of the original bottle and the two replicas, it is clear that the potter of the original vessel must have had knowledge, not only of ceramics as a technique, but an awareness of the mechanisms for the production of sounds. This knowledge and practice enabled the construction of these complex artefacts, and enabled sound to be derived from the hydraulic action, and fufil the need for the 'automation' of sound.

In addition, it is possible that this potter was an important person in the social hierarchy, because, as through these objects, it would be possible to maintain and transmit culture. The transmission of cultural knowledge through these bottles is evident in their design, decoration, size and shape, all which allow us to determine the possible cultural practices (rituals, funerary, festive, community participation etc.) used at that time. Through the traces left in the clay, the possible manufacturing techniques used can be determined such as construction by means of slab, string technique, slip technique etc; and in certain indigenous communities of the Republic of Ecuador these traditions are continued. By contributing to the technological development, it could be said that the Chorrera potters had established a space for the creative and research performance of acoustic ceramics, which led to the construction of these increasingly complex objects acquiring a symbolic meaning and even a ritual or funerary use.

Lasting approximately 1500 years (Crespo (1966), development was driven by the functional and aesthetic needs of the inhabitants of Chorrera to build these very representative artefacts. Our current research has sought to highlight the *scientific* contribution of this culture, showing the capacity to generate sound in an *automated* way. By simple swinging movements, the sound effects must have been an unprecedented 'magical' spectacle, in which the powers of the spirit of water and air are manifested, in dialogue with the spirits of fire and of the earth embodied in the bottle itself. As de Arce argues (2013, 74) the instrument lends its voice so that the water can sing, made to give expression to the natural song of water. This research has aimed to highlight the duality (so typical of the Andean worldview) of *science and spirituality* contained in this object.

The design of the acoustic structure of this bottle and the precise location of the cavities allow the production of several sounds that change from one to the other simultaneously according to the pressure of the air and the external expansion of the sound. This makes it an object of great technological advancement for the period in which it was produced, and could be considered a great contribution to contemporary acoustic development.

The mastery and knowledge embodied in this object is clear to hear. Applying formal variables to the sound mechanism results in modifications to the sound, and would be the same techniques that were mastered by the Chorrera people. The location of the resonator, the size of the air duct, the perforations of the external resonance chamber and the ways of handling the vessels are elements that allow sound variations that were positively mastered and applied to these objects.

We propose that the sound produced by the original bottle can be compared to the sound made by blue-footed boobies in the breeding season. This comparison would attest to what Crespo (1966) sees as the observation and analysis of nature as an important reference to be considered by the potters of Chorrera in the creation of this type of representation (although de Arce (2015) takes a different view and believes the sound is not necessarily related to the forms represented).

As for the replica bottles, the experiments carried out are very valuable because they show several features. First that the whistle with a plastic sphere with very thin walls only allows the emission of a single sound. Second, with a terracotta sphere with thicker walls (2mm thick), the pressure sound of increasing insufflation jumps to a lower frequency (regime change) but both partial ones have variable (increasing) frequencies. Third, tilting the head of the bird changes the spectrum of sounds and the series of partials becomes inharmonic.

Regarding the original bottle, it should be noted that the phenomenon is singular and anomalous because with increasing direct insufflation, the same sequence of two notes is repeated twice A_5-D_6 (do#$_6$variable). The anomaly is that at higher pressure the fundamental jumps towards a lower regime. This phenomenon is probably due to the fact that it is a complex system in which the perforated cavity of the bird's head encloses the whistle and this acts both as an external resonator and as a filter, modifying the whistle spectrum alone, but it also induces this repetition of almost identical behaviours (2 times a serious-acute jump). In this way the succession of sounds emitted by the vessel really imitates those of a bird very well.

In the tests of the hydraulic system in the replica bottle, a similar effect is achieved with two sounds as well, but the noise of the clicking of the water is added during the oscillating movement of the artefact similar to the sounds made by water in a moving stream.

The size of the replica has no effect on the results from analysis of the acoustic structure. Rather, thanks to these replicas, it has been possible to characterise this structure. The possible changes or sonorous variations owing to the difference in the size of the replica compared with the original were not evaluated with the object of faithfully imitating the sounds produced, but rather to analyse and test the sound structure. For future research, it would be interesting to study how the listener perceives sound from a variety of distances, using the replicas in a natural environment, closer to what might have been the case in the past.

Further work is in progress and includes the study of the internal organological system of this same object; the study of the triple globular anthropomorphic bottle with double whistle from the Bahía-Ecuador culture (belonging to Crespo's phase 6 (1966)); and other related research such as the study of the anthropomorphic flutes of the Bahía culture and the study of the *pututos* or conch shells. It is hoped that the present study creates a point of departure for researchers to continue contributing to the knowledge and practice of ceramics to the reconstruction of the entire evolutionary process of the whistle bottle. It would be interesting to reproduce all six stages as proposed by Crespo (1966) to try and discover the contribution of each one of them to establish and clarify the development of these objects.

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Acknowledgements

Thanks are due to the Ministry of Culture and Patrimony of Ecuador for facilitating our entry into the National Reserve; to Ivett Celi, Sub-secretary of Social Memory; to Esthelina Quinatoa, curator of the National Reserve; Renee Guaitara, Network Coordinator of Museums, National Museum of Ecuador. To the Faculty of Arts of the Central University of Ecuador, for having facilitated the laboratories to accomplish the research; to Jorge Zamora for the collaboration in the initial ceramic process study. To Arnaud Gérard for his contribution in the acoustic analysis. Thanks also to Santiago Ortiz, research assistant.