SPERM WHALE (PHYSETER MACROCEPHALUS) CODAS AND CREAKS IN THE NORTHERN GULF OF MEXICO: CLASSIFICATION, COMPARISON, AND CO-OCCURRENCE

Robin Lorraine Duncan Paulos
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by

Robin Lorraine Duncan Paulos

A Dissertation
Submitted to the Graduate Studies Office
of The University of Southern Mississippi
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy

August 2007
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Abstract of a Dissertation
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The present study set out to classify sperm whale codas recorded by bottom-moored hydrophones in the Northern Gulf of Mexico (NGoM) during July and August of 2001 using protocols similar to those followed in other studies. After classification, comparisons were made between the repertoire identified herein and those identified in other studies, both in the NGoM and in other parts of the world.

This study identified 5,035 codas representing 34 distinct coda types. The similarity in coda patterns between this study and another from the same location, combined with historical sightings and a lack of temporal variability in coda production identified in other studies, supports the theory that a resident population of sperm whales (Physeter macrocephalus) might inhabit the NGoM. Coda types were more similar between the present study and the Apple (2002) analysis also conducted in the same region, than between the present study and those conducted in other areas of the world. Time-of-day and location analyses were also performed on the identified codas. The similarities and differences in coda production also lend support to the premise that the coda repertoire used by sperm whales seems to vary geographically, but remains relatively stable within a group (Weilgart & Whitehead, 1997).
An analysis of the co-occurrence of codas and creaks was also performed with a preliminary examination of creak characteristics. Perhaps the most significant finding in this study relates to the duration of the creaks recorded at all three buoy recording locations. Overall, 98.9% of the creaks in this study had durations less than 4.0 s, an indication that they may be creaks associated with socializing and not foraging. Further support of the theory that much socialization activity was occurring during the present study came from the analysis of the co-occurrence of codas and creaks. Overall, 81.5% of all creaks produced, occurred in the presence of codas; vocalizations most often heard during socialization.

While the findings revealed herein may expand the knowledge base regarding coda repertoires and acoustic behavior of sperm whales in the NGoM, further research is called for to supplement the existing data in an effort to gain a better understanding of sperm whale vocal behavior during foraging, social, and other contexts in the NGoM.
DEDICATION

This long road was not embarked upon nor traveled alone. The all-consuming nature of the process affects not only the person pursuing the degree, but all those that care about them. This dissertation is respectfully and lovingly dedicated to those people who made it possible for me to reach my destination.

To my parents, Robert and Jennie Duncan, a lifetime of encouragement and support has given me the courage to take on the challenge. Thank you for providing me with the fortitude to begin the journey.

To Hope...you have always been, and will always be, my inspiration. I think about how easy it would be for you to give up, but instead you curse the darkness, embrace the challenge, and find your way. Thank you for being my light.

Terry, there is so much to thank you for. You were the impetus of this journey. You asked me “if you could do anything, what would it be?” Then, you made my dream a reality. Your sacrifices have been many and I am indebted to you for each and every one. Without your help I would never have been able to embark upon, much less complete, this journey. Thank you for being my staff for support, my map for guidance, and the voice in my head that drove me to finish.

"The real voyage of discovery consists not of seeking new landscapes but in having new eyes"

Marcel Proust
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information about her research but also the practice of sharing her data, a behavior that is
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including me in your world!

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done to make my graduate school experience a positive one would take far too many
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LIST OF ABBREVIATIONS

EARS – Environmental Acoustic Recording System

EARS 1 – (E1) Deployed in 1,000 m of water with the hydrophone at 950 m
EARS 2 – (E2) Deployed in 800 m of water with the hydrophone at 750 m
EARS 3 – (E3) Deployed in 600 m of water with the hydrophone at 550 m
Gb – Gigabytes

NGoM – Northern Gulf of Mexico

ICI – Inter-click interval

IPI – Inter-pulse interval

LADC – Littoral Acoustic Demonstration Center

MMS – Mineral Management Service

NAVOCEANO – Naval Oceanographic Office

NRL-SSC – Naval Research Laboratory at Stennis Space Center

SWAMP – Sperm Whale Acoustic Monitoring Program

UNO – University of New Orleans
CHAPTER I
INTRODUCTION

The sperm whale (*Physeter macrocephalus*) may be one of the most familiar cetaceans in the world thanks to the classic epic *Moby Dick* by Herman Melville (1851). The sperm whale was not only a favorite of literary aficionados, but also of Yankee whalers of the Eighteenth century. The sperm whale was a prize catch as a result of their valuable spermaceti oil, used as lamp fuel, machinery lubricant, and in cosmetics and soap (Berzin, 1971; Rice, 1989; Townsend, 1935; Watkins, 1977). These whales were nearly hunted into extinction and were harvested in every ocean of the world (Townsend, 1935) until they were placed on the Endangered Species List in 1973 (U.S. Fish and Wildlife Service, 1973) protecting them in US waters. In 1985, they were given full protection by the International Whaling Commission; however, Japan continued to harvest sperm whales in the western North Pacific until 1988 (Whitehead, 2003).

Distribution, Life History, and Social Structure

Although endangered, sperm whales are one of the most widely distributed animals on Earth, found at the ice edges at both poles and at all latitudes in between (Berzin, 1971; Rice, 1989). Generally seen in deeper areas of the ocean, they are frequently found in areas the whalers termed “grounds” (Townsend, 1935). These grounds often coincide with areas of increased primary and secondary productivity associated with regional upwelling (Gulland, 1974; Jaquet & Whitehead, 1996; Jaquet, Whitehead, & Lewis, 1996). In addition, the distribution of females differs from that of the males as the whales age.
Following a gestation period of about 15 months, a sperm whale is born into a matrilineal society (Best, Canham, & Macleod, 1984; Whitehead & Weilgart, 2000). Very young sperm whales of both sexes generally stay within their mother’s social unit; however, between the ages of three and 15, males leave and form bachelor groups (Rice, 1989). As the males age, these bachelor groups become smaller and the maturing males move toward higher latitudinal elevations. The older males (in their 40’s and 50’s) are more solitary and may be seen singly near the ice edges in both hemispheres (Rice, 1989). In contrast, the females spend most, if not all, of their lives with their female kin. Best (1979) suggests this grouping of extended family may have a dual function: protection and care of calves, and cooperative feeding.

Male sperm whales move to higher latitudes as they mature, with the largest males often found in waters close to the ice edges. Therefore, the home range of the males is much larger than that of the females who tend to stay in tropical to temperate waters (Martin, 1982). The older males (over 25 years old) migrate to the tropical breeding grounds to interact with the female and immature groups. Although little is known of the frequency, duration or extent of these migrations, there are seasonal peaks in reproductive activity (Whitehead, 2003). While at the breeding grounds, more than one male may associate with a female/immature group at any one time (Whitehead, 1993). Occasional fights between males at these breeding grounds do occur, however such fights are rare (Best, 1979; Kato, 1984). Males that share a breeding area may assess each other using “slow clicks” (see section on communication), thus preventing unnecessary combat (Gordon, 1991; Weilgart & Whitehead, 1988).
Female and immature sperm whales of both sexes are commonly found at latitudes of less than 40° except in the north Pacific where they have been sited at latitudes up to 50° (Rice, 1989). The home range of the female sperm whale is approximately 1,000 km (Best, 1979; Dufault & Whitehead, 1995); however, they occasionally will travel across ocean basins spanning several thousand kilometers (Kasuya & Miyashita, 1988).

Several hierarchical levels of social/spatial organization exist for the females ranging from the most transitory “clusters” through the most long-lasting “units” (Table 1; Paterson, 1986; Whitehead, Waters, & Lyrholm, 1991; Whitehead & Weilgart, 1990).

Table 1

Social Group Dimensions for Sperm Whales

<table>
<thead>
<tr>
<th>Social Group</th>
<th>Number of Animals</th>
<th>Duration of Association</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster</td>
<td>2 +</td>
<td>minutes to hours</td>
</tr>
<tr>
<td>Group</td>
<td>20 - 30</td>
<td>hours to days</td>
</tr>
<tr>
<td>Aggregation/ Super-aggregation</td>
<td>40 +</td>
<td>days to months (depending on prey availability)</td>
</tr>
<tr>
<td>Concentration</td>
<td>~ 1,000</td>
<td>months or more (generally corresponds to grounds)</td>
</tr>
<tr>
<td>Family unit</td>
<td>~ 10</td>
<td>&gt; 12 years</td>
</tr>
<tr>
<td>Vocal clan</td>
<td>1,000’s</td>
<td>at least 6 years (potentially much longer)</td>
</tr>
</tbody>
</table>

Whales are often seen in clusters while foraging or socializing at the surface. These clusters range from 20 to 200 m across and may reduce the possibility of predation through increased vigilance. Active clustering by sperm whales may also be a way to
maintain social bonds through spatial proximity and temporal synchrony (Whitehead, 2003).

The "group" is defined as "a set of animals moving together in a coordinated fashion over periods of at least hours" (Whitehead, 2003; p. 213). Estimating the size of a group of sperm whales is difficult because of the inability to maintain visual contact with the animals as they engage in lengthy dives. However, several methods are in use to minimize potential error. These methods include observing the animals for several hours at a time and using a mark-recapture method and lagged association rates to estimate the typical group size (Whitehead, 2003). Even so, group size can vary substantially around the mean when examining different geographical locations as well as the same population over time.

The terms "aggregation", "super-aggregation", and "concentration" are based on prey availability and, although are generally used in reference to females and immatures, may also apply to non-breeding males. These terms are used primarily to refer to whales grouped for extrinsic factors (distribution of food) as opposed to those grouped for a more intrinsic reason such as socialization (Paterson, 1986; Whitehead & Weilgart, 1990; Whitehead et al., 1991).

The "family unit" or "unit" seems to be the fundamental element of sperm whale society (Christal, Whitehead, & Lettevall, 1998). They consist of long-term companions of one or more matrilines within a small geographic range (~0.5 km). Units often combine in tropical to subtropical waters to form the above-described "groups".

The purported functions of the unit include reduction of predation risk and, perhaps more specific to the long-term nature of the inter-individual relationships,
communal care of the young. Immature whales associate with different individuals within the family unit, often “switching off” to another animal at the surface when a companion dives; however, the strongest association is with its mother (Gordon, 1987; Whitehead, 1996). There is other evidence of allomaternal care among female sperm whales. Whalers often found instances of more lactating females than calves in a group (Best et al., 1984). Combined with behavioral observations of newborn sperm whale calves (Weilgart & Whitehead, 1986), this suggests that alloparenting exists within sperm whale communities.

Rendell and Whitehead (2003) introduced the concept of another category of social structure, the “vocal clan”, based on an acoustic grouping methodology. Clans have a range that spans thousands of kilometers and may overlap that of other clans. They contain thousands of whales that share a coda repertoire (see section on communication for more information about codas). This coda repertoire seems to be stable for a period of at least six years—potentially over generations (Rendell & Whitehead, 2005). Units seem to form groups preferentially with other units of the same clan; Rendell and Whitehead (2005) suggest that they may be the result of cultural transmission of vocal patterns.

Sperm whales spend approximately one-quarter of their time socializing or resting at or near the surface of the water (Whitehead & Weilgart, 1991). Off the Galápagos, periods of social behavior peak in the late afternoon and usually last from an hour up to five or six hours (Whitehead & Weilgart, 1991). During these social periods, the whales generally move slowly in no specific direction, often touching or stroking one another with the jaw or pectoral fin (Whitehead & Weilgart, 2000). While resting, tightly
clustered groups of whales may lie motionless and silent for several hours at a time (Whitehead & Weilgart, 2000).

The remaining three-quarters of a sperm whale’s time is spent foraging at depth with intervals of respiring at the surface (Whitehead & Weilgart, 1991). Sperm whales are the largest of the toothed whales (suborder Odontoceti) and therefore have substantial energy requirements (Lockyear, 1981). Despite these energy requirements, they eat small food items (primarily cephalopods) that have little nutritional value (Clarke, 1980; Kawakami, 1980). In the northern North Atlantic, North Pacific, around New Zealand, and off Iceland, the sperm whale diet also includes fish. However, fish (mainly medium to large bottom-dwellers) are a larger part of the diet of the males than of the females in these areas (Rice, 1989).

The foraging pattern of sperm whales differs geographically; however, a general pattern would include a dive ranging from 30 to 60 minutes in duration followed by approximately eight minutes spent at the surface respiring (Gordon & Steiner, 1992; Papastavrou, Smith, & Whitehead, 1989; Watkins, Daher, Fristrup, Howald & di Sciara, 1993; Watwood, Miller, Johnson, Madsen, & Tyack, 2006). Groups that are composed of females and immature animals stagger their dives such that there are shorter periods of time with no adults at the surface (Whitehead, 1996). The mature and maturing males generally forage independently (Gordon, Leaper, Hartley, & Chappell, 1992; Whitehead, Waters, & Lyholm, 1992) with some degree of coordination of movement over an area of several kilometers (Christal & Whitehead, 1997).

In general, no consistent diurnal pattern of sperm whale feeding has been identified (Clarke, 1980). The whales off of the Galápagos Islands, however, seem to be
an exception. These whales appear to forage more at night and in the morning with less foraging occurring in the afternoon (Whitehead & Weilgart, 1991). There also seems to be little difference in dive depths between day and night (Papastavrou et al., 1989).

Communication

Sperm whales are a social species, and like other social animals must have a system of communication in order to relay information about predators, prey or behavioral state. There are several modalities of sending and receiving signals that social animals may employ. These modes of communication may be visual, chemical, electric, tactile, or auditory (Dudzinski, Thomas, & Douaze, 2002; Tyack, 2000). The physical characteristics of the ocean environment limit the usefulness of some of these modalities. Suspended particulate matter in the water limits visual range. Biological chemicals (i.e., hormones, urine, etc.) rapidly dilute upon entering the water rendering the chemical modality inefficient. Electric and tactile modes of communication require the sender and receiver to be in close proximity to one another. However, physical contact is not always necessary for these last two means of signal exchange to occur. Some freshwater and marine fish can sense electrical signals from a limited distance (Hopkins, 1977) and the burst-pulse sounds of a dolphin “buzz” may be felt several meters away from the sender (Herzing, 2000).

The sperm whale, like other aquatic-dwelling animals, probably relies on the acoustic channel for most of its communicative exchanges (Tyack, 2000; Whitehead & Weilgart, 2000). In the oceanic environment, sound is the most efficient means of communication, especially for communicating over long distances. Whales may hear
another whale tens of kilometers away. This is especially true of cetaceans that utilize lower frequency vocalizations (low frequency sounds propagate farther than high frequency sounds in water) such as the finback whale (Balaenoptera physalus) (Watkins, Tyack, Moore, & Bird, 1987) and the blue whale (Balaenoptera musculus) (Cummings & Thompson, 1971; Edds, 1982). However, for some cetaceans such as the Boto (Inia geoffrensis) and the Ganges River dolphin (Platanistida gangetica), the acoustic channel plays an important role in communication over shorter ranges as well. These dolphins must rely heavily on acoustic information because of turbid or murky water conditions and reduced visual acuity (Berta & Sumich, 1999; Norris, 1969).

In general, odontocetes produce vocalizations that are whistles, pulsed sounds (such as clicks), or both (Richardson, Green, Malme, & Thomson, 1995). Moreover, it is generally the species that use whistles that are social and assemble in groups (Tyack, 1986). However, sperm whales are an exception. They are social but produce only clicks (Backus & Schevill, 1966; Watkins, Moore, & Tyack, 1985a; Watkins & Schevill, 1977a). These clicks may assist in navigation as well as in maintaining herd integrity during foraging at depth or when the pod is scattered at the surface (Watkins et al., 1985a; Watkins & Schevill, 1977a, 1977b; Whitehead & Weilgart, 1990).

The Anatomy of Click Production

The body of a sperm whale is not unlike that of other cetaceans (Berta & Sumich, 1999). Nonetheless, sperm whales possess a feature not found in other species, the spermaceti organ, thought to be involved in the production of clicks. The spermaceti
organ dominates the sperm whale head and comprises 25-33% of the animal’s body length (Whitehead, 2003). It is somewhat barrel-shaped and is situated anterior and dorsal to the sperm whale’s skull (Figure 1).

Figure 1. Sagittal view of the internal structures of the sperm whale head (adapted and redrawn from Kazár in Whitehead 2003, p. 9).

The spermaceti organ is encased in a muscular sheath and surrounds a mass of spongy tissue saturated in a lipid substance called spermaceti oil. The skull forms a concave structure and is situated at the posterior of the spermaceti organ. An air-filled structure (the frontal air sac) separates the skull from the spermaceti organ. The frontal air sac is connected to the right nasal passage, which runs beneath the spermaceti organ and above a second mass of oil-soaked tissue. The whalers called this mass of tissue that contains a series of acoustic lenses, the “junk”. The right nasal passage is connected at the anterior of the spermaceti organ to the distal air sac. This air-filled sac is also connected to the blowhole and is the location for a valve-like structure called the museau
The whale breathes through the left nasal passage that runs directly from the blowhole to the main airway passage (Cranford, 1999, Madsen, 2002).

A proposed function of the spermaceti organ is to assist in click production (Cranford, 1999; Madsen, 2002; Norris & Harvey, 1972). A pulse of sound is initially produced by air being forced through the museau du singe. The pulse travels through the spermaceti organ and is reflected off of the frontal air sac. Part of this reflected pulse is then redirected into the junk and broadcast into the ocean through the acoustic lenses. Another part of the reflected pulse travels back and forth through the spermaceti organ resulting in a secondary pulse. This secondary pulse is then redirected into the junk and out into the water. This process may occur several times resulting in clicks that contain three or more pulses. Several authors propose that the interval between pulses (the interpulse interval or ipi) may be used as a way to infer the size of the whale (Adler-Fenchel, 1980; Goold, 1996; Gordon, 1991; Marcoux, Whitehead, & Rendell, 2006; Norris & Harvey, 1972; Rendell & Whitehead, 2004).

**Clicks and Their Patterns**

Sperm whale clicks are sharp-onset, broadband, impulsive vocalizations that range in frequency from <100 Hz to 30 kHz (Richardson et al., 1995) and often contain energy in lower frequencies (<1 kHz) than other cetacean clicks (Cranford, 1999). The clicks can be very powerful (up to 223 dB re 1 μPa @ 1 m) and can be strongly directional (Møhl, Wahlberg, Madsen, Miller, & Surlykke, 2000; Thode, Mellinger, Stiensessen, Martinez, & Mullin, 2002). Sperm whale clicks can generally be assigned to
one of four categories based on the pattern of clicks and timing of the intervening
intervals (Backus & Schevill, 1966; Jaquet, Dawson, & Douglas, 2001): “usual” or
“regular clicks” are the most common type of click heard and have an interclick interval
(ici) of 0.5 to 1 sec, “slow clicks” have an ici of approximately 5 to 7 secs (Weilgart &
Whitehead, 1988), “creaks” are rapid clicks (up to 220 clicks per second) (Gordon,
1987), and “codas” are made up of clicks that have variable repetition rates but occur in a
repetitive, rhythmic pattern (Watkins, Moore, & Tyack, 1985b; Watkins & Schevill,
1977b; Worthington & Schevill, 1957). Sperm whales may produce these clicks in
various patterns in a variety of situations.

In short, echolocation and communication are the two functions attributed to
sperm whale clicks. Although it is likely that one of these functions is primary, it is also
possible that some patterns may be associated with both echolocation and communication
(Backus & Schevill, 1966).

Usual Clicks. Usual clicks (Figure 2) are the most common type of click
produced by sperm whales and are generally produced in long trains of regularly spaced,
successive clicks (Backus & Schevill, 1966; Jaquet et al., 2001; Whitehead et al., 1992).
Figure 2. Spectrograph image illustrating usual clicks from the EARS 3 buoy recording file 14352231.

Trains of usual clicks are typically interspersed with periods of silence as well as other vocalization patterns such as creaks, codas, or slow clicks (Whitehead, 2003). Usual click trains are commonly made by sperm whales during deep dives and are often heard as a cacophony of sound as usual click trains from several whales are superimposed on one another. This is especially true within groups of females and immatures (Whitehead, 2003). Usual clicks range from 0.2 – 32 kHz with the major emphasis in the 2 – 6 kHz range and relative power approximately 175 – 180 dB re 1 μPa @ 1 m (Backus & Schevill, 1966; Watkins, 1977, 1980; Weilgart & Whitehead, 1988). Usual clicks may last from 10 seconds to 50 minutes and may alternate with periods of 20 seconds to 30 minutes of silence (Mullins, Whitehead, & Weilgart, 1988; Watkins, 1980).
The vast majority of sperm whale scientists (including Backus & Schevill, 1966; Goold & Jones, 1995; Gordon, 1987; Jaquet et al., 2001; Madsen, Wahlberg, & Möhl, 2002; Möhl et al., 2000; Norris & Harvey, 1972; Weilgart, 1990) interpret usual clicks as echolocation, as used in navigation or in searching for prey. Watkins (1980) does not agree with this consensus. He proposed that the primary function of usual clicks is not echolocation but instead a type of “contact call” (see also Watkins et al., 1985a). However, in light of recent findings regarding the directionality of the clicks (Möhl et al., 2000; Thode et al., 2002), irregularity of clicks before creaks (Jaquet et al., 2001), and the duration of the pulses within the click (Madsen, 2002), Watkin’s arguments are refutable (see Whitehead, 2003).

Slow Clicks. Slow clicks, also called “clangs” by Gordon (1987), are generally produced by mature or maturing males and are primarily heard on the breeding grounds, both at the surface and at depth (Weilgart & Whitehead, 1988). Rarely, slow clicks have been documented on the feeding grounds at higher latitudes (Jaquet et al., 2001; Mullins et al., 1988).

The slow click is a loud, ringing click that is repeated about every five to eight seconds. Its lower repetition rate, duration, and frequency structure distinguish the slow click from the clicks that make up a usual click train. The slow click emphasizes “ringing” and low frequencies (Goold, 1999; Gordon, 1987; Weilgart & Whitehead, 1988) and has less pronounced directionality (Madsen et al., 2002). Slow clicks generally seem louder to a human listener than usual clicks or creaks (Goold, 1999;
Gordon, 1987; Weilgart & Whitehead, 1988), possibly as a result of their lower frequencies and directionality.

Weilgart & Whitehead (1988) suggest that slow clicks in long sequences might be used to convey information about the reproductive fitness of the sender. Their function may be to allow other males to assess or avoid the producer of the sound (Whitehead, 1993) similar to many other male-specific vocalizations (see Bradbury & Vehrencamp, 1998). If the signal was an “honest” one (not able to be faked) that indicated the size or other attributes of the male, it would allow other males or females to react appropriately to the sender of the signal. In this way, the slow click could be a vital component of a system of male-male competition and/or of female choice (Whitehead, 2003).

The slow clicks produced by males during surface intervals on the high-latitude feeding grounds have been called “surface clicks” by Jacquet and colleagues (2001). They suggest that these clicks could have a different function than those produced in the company of females. Similarly, slow clicks have been heard in other circumstances as well. Goold (1999) heard numerous slow clicks (but with an ici of 2 – 3 s rather than the 5 – 8 s that is normal) from a group of entrapped males who were being shepherded out from the enclosed waters of Scapa Flow in the Orkney Islands. This same type of slow click (with a shorter ici) was also heard produced by whales in the northern Gulf of Mexico (R. Paulos, unpublished data). The sex of the animals that produced these sounds and the behavioral context in which they occurred remain unknown.

Creaks. Creaks are a series of rapidly emitted clicks producing a sound much like the groaning of an old door hinge (Figure 3). They are produced by sperm whales both at
depth (when foraging) and at the surface (in social contexts); therefore, a dual function likely exists (Gordon, 1987; Weilgart, 1990).

Figure 3. Spectrograph image illustrating a creak (between black arrows) from the EARS 3 buoy recording file 08652121.

When produced at depth, the click rate may accelerate over the course of the creak. This is generally interpreted as the sperm whale homing in on its prey (Whitehead, 2003).

Surface creaks are sometimes called “coda-creaks” (Weilgart, 1985, 1990), “rapid clicks,” or “chirrups” (Goold, 1999; Gordon, 1987). These creaks are usually shorter (0.1 – 4 s; Weilgart, 1985, 1990) than foraging creaks (which may last up to 45 s) and have
longer clicks (50 – 100 ms) than the foraging creaks (5 – 40 ms) (Gordon, 1987). Therefore, these socializing creaks seem to be appropriate for a brief echoic assessment of objects at ranges of up to about 30-80 m. (Whitehead, 2003). A whale directing a creak at a social partner may be assessing their movements, orientation, or even their internal organs (Whitehead, 2003). In the Atlantic spotted dolphin (*Stenella frontalis*), click trains are associated not only with echolocation but in situations of courtship, discipline, foraging/feeding, and play (Dudzinski, 1998; Herzing, 2000). Herzing (2000) suggested that this type of vocalization may have a tactile effect on the recipient that ranges from pleasure to pain depending on the intensity.

**Codas.** Codas are stereotyped sequences of sperm whale clicks lasting from approximately 0.2 – 5 s, which occur in a pattern of about three to 20 clicks (Figure 4; Whitehead, 2003). They are sometimes produced at the end of a usual click train, so in following musical terminology, Watkins and Schevill (1977b) called them “codas.”

Codas are most frequently heard when whales are at or near the surface and are moving slowly in and around one another (Weilgart & Whitehead, 1997; Whitehead & Weilgart, 1991), but are also heard in small numbers during dives (Madsen et al., 2002). Furthermore, they seem to occur only between whales that are in close physical proximity to one another (Watkins & Schevill, 1977a). Codas may be heard by themselves (singularly with no exchange apparent) and in complicated overlapping sequences in which several animals are vocalizing at once (Watkins & Schevill, 1977b). In some cases, a duet-like “echo-coda” has been documented in which two whales make precisely the same coda pattern, offset by about 50 – 100 ms (Weilgart, 1990).
Structurally, the clicks within codas seem to differ from those that make up usual click trains in several ways. The clicks that make up a coda generally have a more pronounced secondary pulse, less directionality, and reduced power than usual clicks (Madsen et al., 2002). Madsen and colleagues suggest that the structural difference in the clicks might be achieved by changing the shape of the distal air sac to allow for more reflections within the spermaceti organ. This would produce a less directional click that would be better suited for communication than for echolocation (Whitehead, 2003).

Several theories regarding the function of codas have been posited over time. In the first report on codas, Watkins and Schevill (1977b) noted that during an exchange between two whales, each animal seemed to prefer one coda type. This led them to

Figure 4. Spectrograph image illustrating three codas (between solid black arrows) and a creak (between dashed arrows) from the EARS 3 buoy recording file 08652121.
suggest that specific coda types identified specific individuals, as in the proposed signature whistles of bottlenose dolphins, *Tursiops truncatus*, (see Caldwell, Caldwell, & Tyack, 1990). However, this proposed function does not seem likely, as individuals produce codas of different types, different individuals produce the same coda type, and in any population there are many fewer coda types than there are whales (Gordon, 1987; Weilgart & Whitehead, 1993; Weilgart & Whitehead, 1997). It is possible that information regarding individual identity may be contained in some aspect of the coda other than the temporal patterning, but data on this topic are limited.

A possible alternative function of sperm whale codas relates to communication. Codas may function to mediate social interactions or reaffirm social bonds while whales are congregated at the surface after a period of foraging (Moore, Watkins, & Tyack, 1993; Weilgart & Whitehead, 1993). A similar type of reaffirmation behavior has been documented in squirrel monkeys (*Saimiri* spp., Symmes & Biben, 1988). Upon reuniting following periods of dispersal while foraging, squirrel monkeys will produce vocal exchanges thought to function in reaffirming social bonds (Symmes & Biben, 1988). Dunbar (1993) posited that human communication, specifically language, developed from this type of pre-hominid grooming as a kind of verbal grooming that could be performed at a distance to maintain the relationships between individuals in the group. In this way, language may have allowed societies to remain cohesive, while reducing the need for physical intimacy.

Codas seem to be used non-randomly within exchanges. In codas recorded off the Galápagos Islands, certain codas tended to initiate exchanges, and some patterns were more likely to follow other coda types (Weilgart & Whitehead, 1993). This “ordering” of
codas within exchanges seems to indicate that communication might be taking place (Weilgart & Whitehead, 1993; Whitehead & Weilgart, 2000); however, what information is being transmitted is unclear.

Further support for the communication function is provided by observations of a young sperm whale calf in captivity. A young calf kept briefly in captivity during rehabilitation produced codas (Watkins, Moore, Clark, & Dahlheim, 1988), but large males rarely do (Goold, 1999; Gordon et al., 1992). Young calves are highly social animals, but large males are not. Therefore, this observation further supports the association between coda production, communication, and sociality (Whitehead, 2003).

Codas appear to be used primarily as intra-group communication, rather than in communication between groups since codas only carry about 2 km and groups are usually separated by much greater distances (Madsen, 2002; Weilgart & Whitehead, 1997; Whitehead, 2003). In addition, there is regional geographic variation in coda types (Weilgart & Whitehead, 1997). Weilgart & Whitehead (1997) suggest that this variation results from the distinctive coda dialects of particular social units, which have preferred geographic ranges. Strong group-specific dialects that persist over a number of years seem to exist (Weilgart & Whitehead, 1997). Furthermore, differences in repertoire have been found in different geographical locations (Apple, 2002; Moore et al., 1993; Pavan et al., 2000; Weilgart & Whitehead, 1993, 1997).

The process of developing a coda repertoire is likely fostered by vocal learning (Weilgart & Whitehead, 1997). Sperm whale calves likely acquire a coda repertoire by listening to the mother or other members of the matrilineal group. Calves develop a repertoire over time, with the youngest calves producing fewer repetitive patterns than
older calves. The older calves produce a larger number of coda patterns which more closely resemble the coda patterns produced by the adults in the group (Watkins et al., 1988). Given the ability of other cetaceans to mimic sounds (Reiss & McCowan, 1993; Richards, Wolz, & Herman, 1984) and the ability of humpback whales (Megaptera novaeangliae) to acquire new songs (Payne, Tyack, & Payne, 1983), it is likely that vocal learning is the mechanism by which sperm whale calves acquire their coda repertoire.

Previous Research

Previous research has uncovered a range in the number of coda categories heard in the presence of sperm whales in numerous studies across the globe (Table 2). In these studies, codas were categorized on the basis of the icis. A coda classified as “regular” would contain regularly spaced clicks, with all icis nearly the same length. For example, a coda that contained 4 regularly spaced clicks (////) is called a “4 regular” or simply a “4” coda. If an ici within a coda was at least 50% longer than the mean interval distances between the other regularly-spaced clicks in that coda, the coda was classified differently. For example, a 4 click coda that contained a delayed click at the end (/// /) would be called a “3+1”. These delayed clicks often occur at the end of the coda (Weilgart & Whitehead, 1993), however a delay at the beginning of the coda is also possible (Drouot & Gannier, 1999; Moore et al., 1993; Weilgart & Whitehead, 1997). If there is little similarity in the spacing between any of the clicks within a coda, that coda was classified according to the number of clicks with the designation “variable” (e.g., 7 variable).
Table 2

**Information Regarding Previous Research on Sperm Whale Codas Worldwide**

<table>
<thead>
<tr>
<th>Source</th>
<th>Site</th>
<th>Year(s)</th>
<th># Codas analyzed</th>
<th># Coda types</th>
<th>Mean duration of codas</th>
<th>Most frequent coda type</th>
<th>% Represented by most frequently observed coda</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple, 2002</td>
<td>NGoM</td>
<td>1992-1997</td>
<td>842</td>
<td>17</td>
<td>-</td>
<td>8 variable</td>
<td>55.9%</td>
</tr>
<tr>
<td>Weilgart &amp; Whitehead, 1993</td>
<td>Galápagos</td>
<td>1985, 1987</td>
<td>1333</td>
<td>23</td>
<td>1,360 ms</td>
<td>5 regular</td>
<td>17.4%</td>
</tr>
<tr>
<td>Moore et al., 1993</td>
<td>SE Caribbean</td>
<td>1981, 1983, 1984, 1987</td>
<td>677</td>
<td>28</td>
<td>1,000 ms</td>
<td>1+1+3</td>
<td>34%</td>
</tr>
<tr>
<td>Pavan et al., 2000</td>
<td>Mediterranean</td>
<td>1985-1996</td>
<td>136</td>
<td>5</td>
<td>908 ms</td>
<td>3+1</td>
<td>98.5%</td>
</tr>
<tr>
<td>Drouot &amp; Gannier, 1999</td>
<td>Ionian &amp; Tyrrhenian Seas</td>
<td>1998</td>
<td>86</td>
<td>6</td>
<td>437 ms</td>
<td>3+1</td>
<td>62.8%</td>
</tr>
</tbody>
</table>

Note: *analysis also included 1993 data; "-" indicates information was unavailable

The Mediterranean Sea has been the site of several studies involving sperm whale coda production (Borsani, Pavan, Gordon, & di Sciara, 1997; Drouot & Gannier, 1999; Pavan et al., 2000). In the Tyrrhenian Sea, all of the codas analyzed were of the same “3+1” (////) pattern (Borsani et al., 1997). It was determined that these codas were produced by at least seven different whales and although recordings were made in different seasons, codas were only heard in the summer. A later investigation into codas produced not only in the Tyrrhenian Sea, but also encompassing recordings from the Ionian and Ligurian Seas, also found the majority of codas (134 of 138) belonging to this same “3+1” pattern. Drouot and Gannier (1999) recorded six distinct coda types in the
Ionian and Tyrrhenian seas (three in each region). The “3+1” pattern identified earlier was present in both sites. However, there was considerable variation in the total duration and click timing within this pattern between the two regions supporting the theory that coda repertoires vary geographically (Weilgart & Whitehead, 1997).

In the southeast Caribbean, Moore and colleagues (1993) reported a total of 28 distinctive coda patterns with over 50% of the codas belonging to one of two patterns: five regularly spaced clicks (/ / / / / ) representing 34% of all codas or a “1+1+3” (/ / / / / ) pattern representing 20% of the total coda production. The number of distinctive coda types reported from this area is similar to the number reported from the Galápagos. In the Galápagos, Weilgart and Whitehead (1993) identified a total of 23 discrete coda patterns. The most common type heard in this region was a pattern of five regularly spaced clicks (19% of all codas fell into this category).

In the Northern Gulf of Mexico, 17 distinct coda types were identified by Apple (2002). The most common type of coda, representing 55.9% of all codas, was the “8 variable” pattern. This pattern is described as having eight unevenly spaced clicks (Apple, 2002). The second most commonly recorded coda had four regularly spaced clicks and represented less than 9% of all codas analyzed.

The Present Study

The current study used acoustic data recorded in the Northern Gulf of Mexico (NGoM) in the summer of 2001 and seeks answers to the following questions:

1. What is the coda repertoire of the sperm whales in the NGoM during the period July 18, 2001 through August 22, 2001?
2. Is there a difference in coda use between EARS buoys?

3. Are there differences in coda use based on the time of day?

4. How does the coda repertoire of these whales compare to the coda repertoires documented in other studies?

5. What is the relationship between the occurrence of codas and creaks?
CHAPTER II

METHODS

Data Acquisition

In the summer of 2001, three bottom-moored environmental acoustic recording system (EARS) buoys were dispatched in the Northern Gulf of Mexico. The Littoral Acoustic Demonstration Center (LADC) was responsible for the acquisition, deployment and retrieval of this recording equipment. LADC is a collaboration between the University of Southern Mississippi (USM), the University of New Orleans (UNO), and the Naval Research Laboratory at Stennis Space Center (NRL-SSC). LADC receives technical support from the Naval Oceanographic Office (NAVOCEANO) and is also associated with the Sperm Whale Acoustic Monitoring Program (SWAMP) through the Mineral Management Service (MMS). The original focus of the project was to investigate ambient noise in the Northern Gulf of Mexico, but the focus was expanded to include an examination of sperm whale acoustic behavior after consultation with SWAMP. The data collected during the summer of 2001 have been used in several studies examining the contributions of marine mammals and offshore drilling to the ambient noise level at the edge of the continental shelf in the Northern Gulf of Mexico (Newcomb et al., 2003; Newcomb et al., 2002a; Newcomb et al., 2002b; Newcomb et al., 2002c; Snyder, Orlin, Schulte, & Newcomb, 2003).

The EARS buoys were designed and manufactured by NAVOCEANO and included omni-directional hydrophone recording systems combined with a mooring apparatus (Figure 5).
The buoys were deployed from a ship on July 16\textsuperscript{th} to July 19\textsuperscript{th}. The deployment site was chosen to optimize LADC's goal of measuring noise propagation up the continental slope, as well as maximizing exposure to the largest concentration of sperm whale sightings in the general area. This area has been identified as an area rich in sperm whale activity, specifically around the 1,000 m depth contour south/southeast of the Mississippi River delta (Mate, Stafford, & Ljungblad, 1994; Würsig, Jefferson, & Schmidley, 2000). The first buoy, EARS 1, was moored at approximately 28° 15' N and 88° 50' W. The other two buoys, EARS 2 and EARS 3, were deployed along a 43 km line from the 200 m contour to just beyond the 1,000 m contour (Figure 6). Total separation between buoys was approximately 25 km with roughly 7 km separating EARS 2 and EARS 3. The buoy closest to land, EARS 3, was located approximately 55 km from the Louisiana shore.
Figure 6. The EARS deployment sites in the Northern Gulf of Mexico. Adapted from image provided by Joal Newcomb.

EARS 1 was moored at a depth of approximately 1,000 m, EARS 2 at 800 m, and EARS 3 at 600 m. Recovery of EARS 1 and 3 occurred on a cruise between August 29th and September 1st. EARS 2 was recovered on a later “rescue” cruise (November 2nd and 3rd) because it became disconnected from its upper float in turbulent seas.

Each EARS buoy continuously recorded acoustic signals with frequencies up to 5,859 Hz for a period of approximately 36 days (digital sampling rate of 11.7 kHz). The data were stored in individual files that were 349.55 seconds long. Each buoy gathered 72 gigabytes (Gb) of acoustic data for a three-buoy total of 216 Gb. A total of 2,592 hours of audio data was examined acoustically and visually.
CHAPTER III

ANALYSES

Preliminary Analyses

The data were stored in binary format with embedded headers and it was necessary to convert them to a format compatible with standard acoustical analysis software before analyses could be performed. Each file was converted to .wav format using a Matlab M-file written by Christopher Walker of the University of Southern Mississippi.

All files were inspected visually and acoustically for codas and creaks using Raven 1.1 (Cornell Laboratory of Ornithology, 2003) and the following parameters: Hann window with 3 dB bandwidth @ 32.9 Hz, brightness 50, contrast 50, standard gamma II color scheme and 10x zoom. Only high quality recordings were selected for measurement. High quality recordings were defined as those with visually distinct clicks and a high signal-to-noise ratio allowing for accurate measurement of the click series. When a file contained potential codas or creaks but also contained many whale vocalizations or much anthropogenic noise (making distinction of clicks difficult), the file was excluded from further analysis.

Preliminary analysis of each coda included measurement (in seconds) of the interclick intervals or icis (intervals between clicks from the beginning of one click to the beginning of the next) in each coda using Raven 1.1. Similarly, prior to subsequent analyses of creaks, the length of each creak was measured (in seconds) from the
beginning of the first click in the creak to the end of the last click in the creak. All subsequent analyses were performed using SPSS 10.0 (SPSS Inc., 1989 - 1999).

Codas

Classification and Repertoire Identification

Following the methodology used in previous studies (Apple, 2002; Moore, et al., 1993; Weilgart & Whitehead, 1993, 1997), codas were categorized based on the number of clicks in the coda and the temporal pattern of the clicks.

Weilgart and Whitehead (1997) used four non-mutually exclusive click classes in their study: short (< 5 clicks), long (> 6 clicks), regular (with equal spaces between clicks), and plus-one (contained a double interval between the last two clicks). They excluded 5 and 6-click codas from analysis based on their length, but included them in analysis based on structure. For example, a coda with 4 evenly spaced clicks was categorized as both short and regular whereas a coda with 5 evenly spaced clicks was only classified as regular. Weilgart and Whitehead (1997) placed clusters containing less than 50 codas in a category they called variable. This term was later used by Apple (2002), but with a different definition.

Apple (2002) utilized a slightly different classification paradigm, incorporating 5 and 6-click codas into the short and long categories, respectively. Two categories were based on the length of the coda (short and long) and three categories were based on its structure (regular, plus-one, and variable). Short codas contained \( \leq 5 \) clicks, long codas contained \( \geq 6 \) clicks, regular codas contained equal icis, plus-one codas contained a double interval between the last two clicks, and variable codas contained unevenly-
spaced, but “rhythmic” clicks. Because of the frequency of codas with a double interval at the beginning of the coda, a fourth category based on structure (one-plus) was added in this study. The codas in the one-plus category would have been considered variable in the paradigm used by Apple. In general, this study utilized Apple’s paradigm for click categorization in an attempt to minimize differences for an accurate comparison.

To determine the coda repertoire of the whales recorded in this study, codas were classified using both the number of clicks in the coda and the structure of the click pattern to determine a click type. For example, 5-click codas were labeled as type: 5R (regular), 5V (variable), 5+1 (plus-one), or 5 1+ (one-plus). Codas with more than 12 clicks were discarded as a result of their rare occurrence. Stepwise K-means cluster analysis was performed on each click group independently (3-click codas, 4-click codas, etc.) with standardized icis (each interval representing a proportion of the whole coda) used as the grouping variables. Each multivariate ici data set (e.g., with 4 ici variables for 5-click codas, 5 variables for 6-click codas, etc.) was classified into 10 clusters so that each cluster contained a similar patterning of clicks. Because of the simplicity of the 3-click clusters, 5 clusters (instead of 10) were used for this cluster group. Determination of the number of clusters to use was based on previous protocol employed by Weilgart & Whitehead (1997). The cluster analysis was followed by discriminant analysis to determine the accuracy of the cluster categorization.

Following a procedure established by Apple (2002), codas were then more broadly grouped for subsequent analyses using a combination of their length (short or long) and their structure (regular, variable, plus-one, one-plus) to create mutually exclusive coda classes. For this study, the following eight classes were created: short
regular, short variable, short plus-one, short one-plus, long regular, long variable, long plus-one, long one-plus. The classes short one-plus and long one-plus were not included in the Apple study. Variation in long versus short codas in the entire data set (all three EARS buoy recordings) was explored using a binomial test. Variation in coda categories (regular, variable, plus-one, and one-plus) was analyzed using a contingency table analysis with all buoys pooled.

Location Analyses

Codas from each EARS location (EARS 1, EARS 2, and EARS 3) were documented and analyzed. Specifically, the type and frequency of coda classes recorded at the three locations were compared using a contingency table analysis because of the categorical nature of the variables.

Time Analyses

Time categories were created by dividing the 24-hour day into quarters and using military time as descriptors: 0000-0559, 0600-1159, 1200-1759, and 1800-2359. Pooling all three locations, differences between coda classes across time-of-day were analyzed. Further examination of each location individually was also conducted between coda classes and time-of-day. Contingency table analyses were utilized for these comparisons.

Repertoire Comparison

The codas identified here were compared with those identified in other studies. The protocols used herein were most closely modeled after those used in the Apple
(2002) study in the Northern Gulf of Mexico. A slight difference in categorization occurred because of the emergence of a category not found in the Apple study.

Overall, the protocol for naming the codas was identical except for the addition of a category \( \text{one-plus} \) in this study. The emergence of a large number of codas with this particular structure (double interval between the first two clicks in the coda) was the impetus for the additional category. These codas would have been placed in the variable category in Apple (2002). Prior to direct comparison, all codas in this study currently in the \text{one-plus} category were moved into the \text{variable} category to increase the efficacy of the comparison.

Direct comparisons were made between the present study and the Apple (2002) study of coda type (5 \text{regular}, 6 \text{variable}, 7 \text{plus-one}, etc.), overall length (\text{short} or \text{long}), coda category (\text{regular}, \text{variable}, and \text{plus-one}), and coda class (\text{short regular}, \text{long variable}, \text{long plus-one}, etc.). A time-of-day comparison was also made between codas from the two studies. All comparisons were analyzed using Z tests for proportions.

A more general descriptive comparison was made between the results of the present study and those found in Weilgart and Whitehead (1993, 1997).

**Codas and Creaks**

*Creak Characteristics*

Creaks were identified visually and aurally using Raven 1.1 and duration measurements transferred to SPSS for further analysis. Creak durations were measured (accurate to \( \pm 0.01 \) s) and were checked for normality using a one-sample Kolmogorov-Smirnov test. Creak durations were examined with all buoys pooled as well as at each
individual buoy location. A Kruskal-Wallis test was performed to determine if differences in creak durations existed between the three buoy locations. Mann-Whitney U was used for the follow-up tests and Holm’s Sequential Bonferroni procedure was used to control for type I error. Additional characteristics of each creak such as day of occurrence (identified using Julian day) and time of occurrence (in one of four time quadrants) were noted.

Creaks that contained coda-like clicks (clicks occurring either before or after the creak with longer ici’s and strongly resembling the clicks in a coda) were placed in categories based on their atypical structure. Differences in the occurrence of each type of creak at each buoy location were noted and analyzed using a contingency table analysis.

Co-occurrence of Codas and Creaks

The co-occurrence of codas and creaks was also examined. As the co-occurrence of these two vocalizations had not been previously examined, a distance between creak and coda had to be defined to determine whether or not a coda occurred in the “presence” of a creak. A coda was considered “present” if it occurred in the same file in which the creak was heard. For the sake of consistency and because of the uncertainty involved in the timing of the lag between files recorded by EARS buoys, the inclusion of whole files (as opposed to trying to measuring across files) was optimal. Measurements of the distance between the onset of the creak and the onset of the coda closest in proximity, before as well as after the creak occurred, were made. Furthermore, the number of clicks that these pre- and post-creak codas contained was noted.
Further analyses of differences between buoys and whether or not codas were present were also conducted. Overall, differences between time of day and whether or not codas were present were examined using contingency table analyses. These analyses were conducted first on all buoys pooled, then on each individual buoy location. Potential differences in creak duration when codas were present versus absent were examined using two-sample Kolmogorov-Smirnov tests. This analysis was conducted on each individual buoy location. Lastly, contingency table analyses were used to determine if there was a difference between creak type and whether codas were present when all buoys were pooled as well as at each buoy location. Z tests for proportions were used to compare the number of typical versus atypical (those containing coda-like clicks) creaks found in the presence and absence of codas within and across EARS buoy location recordings.
CHAPTER IV
RESULTS
Codas

Classification and Repertoire Identification

A total of 5,035 codas recorded at the three EARS buoy locations and ranging in size from three to 12 clicks were identified (Figure 7). Six-click codas were the most frequently encountered, representing 27.63% of all codas. When 6-click and 4-click codas were combined, they represented 50.85% of all codas. The four most common coda groups (6-click, 4-click, 7-click, and 5-click) together represent 81.31% of all codas identified in this study.

Figure 7. Variation in the number of clicks in codas recorded at all three buoy locations.
The 5,035 codas were classified into 34 types (Table 3). Nine codas (six 13-click codas and three 14-click codas) were eliminated from classification because of the small number of clicks in each click group. Encompassing 19.09% of all codas, the type 6V was the most prevalent, with 4V (13.45%) and 7R (11.88%) ranking second and third. Overall, discriminant analysis revealed that 94.5% of codas were properly classified into groups based on their standardized icis (Table 4).
Table 3

Summary of Category Types, Visual Description of Click Patterns, Number of Codas in Each Type, and the Percentage of the Total Coda Repertoire that Each Type Represents

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th># of Codas</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>3R</td>
<td>///</td>
<td>71</td>
<td>1.41 %</td>
</tr>
<tr>
<td>3V</td>
<td>///</td>
<td>193</td>
<td>3.83 %</td>
</tr>
<tr>
<td>2 + 1</td>
<td>///</td>
<td>15</td>
<td>0.30 %</td>
</tr>
<tr>
<td>1 + 2</td>
<td>///</td>
<td>156</td>
<td>3.10 %</td>
</tr>
<tr>
<td>4R</td>
<td>/// ///</td>
<td>408</td>
<td>8.10 %</td>
</tr>
<tr>
<td>4V</td>
<td>/// ///</td>
<td>677</td>
<td>13.45 %</td>
</tr>
<tr>
<td>3 + 1</td>
<td>/// ///</td>
<td>17</td>
<td>0.34 %</td>
</tr>
<tr>
<td>1 + 3</td>
<td>/// ///</td>
<td>67</td>
<td>1.33 %</td>
</tr>
<tr>
<td>5R</td>
<td>/// /// ///</td>
<td>180</td>
<td>3.57 %</td>
</tr>
<tr>
<td>5V</td>
<td>/// /// ///</td>
<td>274</td>
<td>5.44 %</td>
</tr>
<tr>
<td>4 + 1</td>
<td>/// /// ///</td>
<td>50</td>
<td>0.99 %</td>
</tr>
<tr>
<td>1 + 4</td>
<td>/// /// ///</td>
<td>116</td>
<td>2.30 %</td>
</tr>
<tr>
<td>6R</td>
<td>/// /// ///</td>
<td>402</td>
<td>7.98 %</td>
</tr>
<tr>
<td>6V</td>
<td>/// /// ///</td>
<td>961</td>
<td>19.09 %</td>
</tr>
<tr>
<td>1 + 5</td>
<td>/// /// ///</td>
<td>28</td>
<td>0.56 %</td>
</tr>
<tr>
<td>7R</td>
<td>/// /// ///</td>
<td>598</td>
<td>11.88 %</td>
</tr>
<tr>
<td>7V</td>
<td>/// /// ///</td>
<td>171</td>
<td>3.40 %</td>
</tr>
<tr>
<td>6 + 1</td>
<td>/// /// ///</td>
<td>87</td>
<td>1.73 %</td>
</tr>
<tr>
<td>1 + 6</td>
<td>/// /// ///</td>
<td>58</td>
<td>1.15 %</td>
</tr>
<tr>
<td>8R</td>
<td>/// /// ///</td>
<td>75</td>
<td>1.49 %</td>
</tr>
<tr>
<td>8V</td>
<td>/// /// ///</td>
<td>132</td>
<td>2.62 %</td>
</tr>
<tr>
<td>7 + 1</td>
<td>/// /// ///</td>
<td>23</td>
<td>0.46 %</td>
</tr>
<tr>
<td>1 + 7</td>
<td>/// /// ///</td>
<td>10</td>
<td>0.20 %</td>
</tr>
<tr>
<td>9R</td>
<td>/// /// ///</td>
<td>24</td>
<td>0.48 %</td>
</tr>
<tr>
<td>9V</td>
<td>/// /// ///</td>
<td>124</td>
<td>2.46 %</td>
</tr>
<tr>
<td>8 + 1</td>
<td>/// /// ///</td>
<td>5</td>
<td>0.10 %</td>
</tr>
<tr>
<td>1 + 8</td>
<td>/// /// ///</td>
<td>13</td>
<td>0.26 %</td>
</tr>
<tr>
<td>10R</td>
<td>/// /// ///</td>
<td>36</td>
<td>0.71 %</td>
</tr>
<tr>
<td>10V</td>
<td>/// /// ///</td>
<td>9</td>
<td>0.18 %</td>
</tr>
<tr>
<td>11R</td>
<td>/// /// ///</td>
<td>13</td>
<td>0.26 %</td>
</tr>
<tr>
<td>11V</td>
<td>/// /// ///</td>
<td>14</td>
<td>0.28 %</td>
</tr>
<tr>
<td>1 + 10</td>
<td>/// /// ///</td>
<td>4</td>
<td>0.08 %</td>
</tr>
<tr>
<td>12R</td>
<td>/// /// ///</td>
<td>8</td>
<td>0.16 %</td>
</tr>
<tr>
<td>12V</td>
<td>/// /// ///</td>
<td>16</td>
<td>0.32 %</td>
</tr>
</tbody>
</table>

Total 5,035 100.00 %

Note: The visual description for each variable (V) type is only one example of several forms the variable coda might take.
Table 4

Summary of Discriminant Analysis Results, Indicating Number and Percentage of Codas that were Correctly Grouped Using Cluster Analysis.

<table>
<thead>
<tr>
<th>Coda Group</th>
<th># of Codas</th>
<th>% Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-click codas</td>
<td>435</td>
<td>95.6 %</td>
</tr>
<tr>
<td>4-click codas</td>
<td>1,169</td>
<td>90.4 %</td>
</tr>
<tr>
<td>5-click codas</td>
<td>620</td>
<td>95.6 %</td>
</tr>
<tr>
<td>6-click codas</td>
<td>1,391</td>
<td>92.9 %</td>
</tr>
<tr>
<td>7-click codas</td>
<td>914</td>
<td>95.4 %</td>
</tr>
<tr>
<td>8-click codas</td>
<td>240</td>
<td>95.8 %</td>
</tr>
<tr>
<td>9-click codas</td>
<td>166</td>
<td>89.8 %</td>
</tr>
<tr>
<td>10-click codas</td>
<td>45</td>
<td>95.6 %</td>
</tr>
<tr>
<td>11-click codas</td>
<td>31</td>
<td>93.5 %</td>
</tr>
<tr>
<td>12-click codas</td>
<td>24</td>
<td>100.0 %</td>
</tr>
<tr>
<td>Total</td>
<td>5,035</td>
<td></td>
</tr>
</tbody>
</table>

Average 94.5 %

Overall, more long codas than short codas were identified (Figure 8). The short codas represent 44 % of all codas, whereas long codas represent 56 %. A binomial test indicated that there were more long codas than would be expected by chance alone (N short = 2,224, N long = 2,811, p < .001).
A contingency table analysis of coda categories indicated that there was a significant difference in the frequency of regular versus variable versus plus-one versus one-plus codas when all buoys were pooled, $\chi^2 (3, N=5,035) = 3,026.4, p < .001$.

Regular codas represented 36.0% of all codas identified, variable codas 51.1%, plus-one 3.9%, and one-plus codas 9.0% (Figure 9).
Figure 9. Variation in the number of codas in each of the four coda categories.

A contingency table analysis of coda classes (combination of length and category) revealed that there was a significant difference in the occurrence of short regular, short variable, short plus-one, short one-plus, long regular, long variable, long plus-one, and long one-plus when all buoys were analyzed together, $\chi^2 (7, N = 5,035) = 3,327.8, p < .001$. When both regular (short regular and long regular) and both variable classes (short variable and long variable) are combined, 87.1 % of all codas are accounted for (Figure 10).
Location Analyses

Codas were recorded at all 3 EARS buoy locations and the classes represented at each location were identified (Figure 11). Overall, 22.0 % of all codas were identified at EARS 1 (depth: 1,000 m), 38.7 % at EARS 2 (depth: 800 m), and 39.3 % at EARS 3 (depth: 600 m). Z tests for proportions revealed significant differences between EARS 1 and EARS 2, $Z = -18.29$, $p < .001$, and between EARS 1 and EARS 3, $Z = -18.87$, $p < .001$. Note: EARS 1 was situated farthest out into the Gulf and moored in the deepest water (see Figure 6). A contingency table analysis of the eight coda classes across the three buoy locations revealed that there was a significant difference in class occurrence, $\chi^2 (14, N = 5,035) = 207.4$, $p < .001$. The most frequently occurring coda class at EARS
1 was long variable with 37.1 %. Long variable was also the most frequently occurring class at EARS 2 (30.3 %). At EARS 3, 26.3 % of all codas belonged in the short variable class. The greatest variation between buoys was observed in the long variable class with a spread of 15.5 % between EARS 1 and EARS 3. This was also the class with the most codas (1,427). Similarly, the least variation was observed in the class with the fewest codas (82), the short plus-one class.

![Graph showing relative frequency of codas at each EARS location](image)

**Figure 11.** Relative frequency of codas at each EARS location that fall into each coda class. For example: 8 % of all codas recorded at E1 were of the short regular variety.

**Time Analyses**

Codas were identified in all four time quadrants at all three buoy locations (Figure 12). Between 0000 and 0559, the majority of codas were identified at the EARS 2 location (41.5 %) followed by EARS 3 (34.8 %) and EARS 1 (23.7 %). Between 0600
and 1159, EARS 3 (600 m) contributed the most codas (54.1%), followed by EARS 1 (1,000 m; 25.6%), and EARS 2 (800 m; 20.3%). From 1200 to 1759, the majority of codas were identified at EARS 2 (46.4%), followed by 43.0% at EARS 3, and 10.6% at EARS 1. From 1800 to 2359 EARS 2 and EARS 3 were nearly equal in their contribution of codas (38.8% and 35.1% respectively), with EARS 1 contributing 26.1%.

Figure 12. Total codas in each time quadrant contributed by each of the buoy locations.

A two-way contingency table analysis of coda class versus time quadrant (with all three EARS locations analyzed together), revealed that there was a significant difference in the number of codas in each class between buoys, $\chi^2 (21, N = 5,035) = 521.2, p < .001$ (Table 5).
Table 5

*Summary of Codas in Classes by Time Quadrant with all EARS Buoy Locations Combined*

<table>
<thead>
<tr>
<th>Coda Class</th>
<th>0000 – 0559</th>
<th>0600 – 1159</th>
<th>1200 – 1759</th>
<th>1800 – 2359</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Reg</td>
<td>193</td>
<td>99</td>
<td>79</td>
<td>288</td>
<td>659</td>
</tr>
<tr>
<td>Short Var</td>
<td>380</td>
<td>250</td>
<td>171</td>
<td>343</td>
<td>1,144</td>
</tr>
<tr>
<td>Short + 1</td>
<td>49</td>
<td>8</td>
<td>11</td>
<td>14</td>
<td>82</td>
</tr>
<tr>
<td>Short 1 +</td>
<td>82</td>
<td>126</td>
<td>55</td>
<td>76</td>
<td>339</td>
</tr>
<tr>
<td>Long Reg</td>
<td>354</td>
<td>71</td>
<td>305</td>
<td>426</td>
<td>1,156</td>
</tr>
<tr>
<td>Long Var</td>
<td>462</td>
<td>111</td>
<td>432</td>
<td>422</td>
<td>1,427</td>
</tr>
<tr>
<td>Long + 1</td>
<td>43</td>
<td>9</td>
<td>12</td>
<td>51</td>
<td>115</td>
</tr>
<tr>
<td>Long 1 +</td>
<td>53</td>
<td>21</td>
<td>6</td>
<td>33</td>
<td>113</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1,616</td>
<td>695</td>
<td>1,071</td>
<td>1,653</td>
<td>5,035</td>
</tr>
</tbody>
</table>

A comparison of the number of codas produced during each time period was conducted between EARS buoy locations (Figure 13). Z tests for proportions revealed that there were fewer similarities than differences in coda production (Table 6).

Only EARS 1 (1,000 m) and EARS 2 (800 m) had similar proportions of codas produced between 0000 and 0559. Only EARS 2 (800 m) and EARS 3 (600 m) exhibited similar proportions of codas between 1200 and 1759. The remainder of the comparisons suggested that the proportion of codas produced during a particular time period differed significantly between buoys.
Figure 13. Relative frequency of codas in each time quadrant at each buoy location. Actual number of codas in each segment is given.

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Table 6

Summary of Z Scores and p Values for Comparisons of the Proportion of Codas Produced in each Time Period Between EARS Buoy Locations

<table>
<thead>
<tr>
<th>Time</th>
<th>EARS buoys Compared</th>
<th>Proportions Compared</th>
<th>Z</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000-0559</td>
<td>E1 vs. E2</td>
<td>.3463 vs. .3441</td>
<td>0.12</td>
<td>p &gt; .05</td>
</tr>
<tr>
<td></td>
<td>E1 vs. E3</td>
<td>.3462 vs. .2840</td>
<td>3.60</td>
<td>p &lt; .001</td>
</tr>
<tr>
<td></td>
<td>E2 vs. E3</td>
<td>.3441 vs. .2840</td>
<td>4.06</td>
<td>p &lt; .001</td>
</tr>
<tr>
<td>0600-1159</td>
<td>E1 vs. E2</td>
<td>.1609 vs. .0723</td>
<td>7.70</td>
<td>p &lt; .001</td>
</tr>
<tr>
<td></td>
<td>E1 vs. E3</td>
<td>.1609 vs. .1900</td>
<td>-2.02</td>
<td>p &lt; .05</td>
</tr>
<tr>
<td></td>
<td>E2 vs. E3</td>
<td>.0723 vs. .1900</td>
<td>-10.91</td>
<td>p &lt; .001</td>
</tr>
<tr>
<td>1200-1759</td>
<td>E1 vs. E2</td>
<td>.1022 vs. .2549</td>
<td>-10.15</td>
<td>p &lt; .001</td>
</tr>
<tr>
<td></td>
<td>E1 vs. E3</td>
<td>.1022 vs. .2329</td>
<td>-8.95</td>
<td>p &lt; .001</td>
</tr>
<tr>
<td></td>
<td>E2 vs. E3</td>
<td>.2549 vs. .2329</td>
<td>1.60</td>
<td>p &gt; .05</td>
</tr>
<tr>
<td>1800-2359</td>
<td>E1 vs. E2</td>
<td>.3906 vs. .3287</td>
<td>3.44</td>
<td>p &lt; .001</td>
</tr>
<tr>
<td></td>
<td>E1 vs. E3</td>
<td>.3906 vs. .2931</td>
<td>5.53</td>
<td>p &lt; .001</td>
</tr>
<tr>
<td></td>
<td>E2 vs. E3</td>
<td>.3287 vs. .2931</td>
<td>2.41</td>
<td>p &lt; .05</td>
</tr>
</tbody>
</table>
Repertoire Comparison

*Apple (2002).* A direct comparison between the codas identified in the Apple (2002) study and those identified in this study was conducted. Prior to direct comparison with the Apple study, all codas in the present study identified as belonging in the *one-plus* category were moved into the *variable* category in an effort to more closely imitate the Apple protocols. After this adjustment, 26 coda types were recognized in this study compared to 17 in Apple (2002) (Table 7).
Table 7

*Coda Types Identified in the Present Study and in Apple (2002). The Number of Each Type of Coda is Presented Along with the Representative Percentage of all Codas Within each Particular Study.*

<table>
<thead>
<tr>
<th>Type</th>
<th>Present Study</th>
<th>Apple (2002)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># of Codas</td>
<td>%</td>
</tr>
<tr>
<td>3R</td>
<td>71</td>
<td>1.41 %</td>
</tr>
<tr>
<td>3V</td>
<td>349</td>
<td>6.93 %</td>
</tr>
<tr>
<td>2 + 1</td>
<td>15</td>
<td>0.30 %</td>
</tr>
<tr>
<td>4V</td>
<td>744</td>
<td>14.78 %</td>
</tr>
<tr>
<td>3 + 1</td>
<td>17</td>
<td>0.34 %</td>
</tr>
<tr>
<td>5R</td>
<td>180</td>
<td>3.57 %</td>
</tr>
<tr>
<td>5V</td>
<td>390</td>
<td>7.75 %</td>
</tr>
<tr>
<td>4 + 1</td>
<td>50</td>
<td>0.99 %</td>
</tr>
<tr>
<td>6R</td>
<td>402</td>
<td>7.98 %</td>
</tr>
<tr>
<td>6V</td>
<td>989</td>
<td>19.64 %</td>
</tr>
<tr>
<td>5 + 1</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>7R</td>
<td>598</td>
<td>11.88 %</td>
</tr>
<tr>
<td>7V</td>
<td>229</td>
<td>4.55 %</td>
</tr>
<tr>
<td>6 + 1</td>
<td>87</td>
<td>1.73 %</td>
</tr>
<tr>
<td>8R</td>
<td>75</td>
<td>1.49 %</td>
</tr>
<tr>
<td>8V</td>
<td>142</td>
<td>2.82 %</td>
</tr>
<tr>
<td>7 + 1</td>
<td>23</td>
<td>0.46 %</td>
</tr>
<tr>
<td>9R</td>
<td>24</td>
<td>0.48 %</td>
</tr>
<tr>
<td>9V</td>
<td>137</td>
<td>2.72 %</td>
</tr>
<tr>
<td>8 + 1</td>
<td>5</td>
<td>0.10 %</td>
</tr>
<tr>
<td>10R</td>
<td>36</td>
<td>0.71 %</td>
</tr>
<tr>
<td>10V</td>
<td>9</td>
<td>0.18 %</td>
</tr>
<tr>
<td>11R</td>
<td>13</td>
<td>0.26 %</td>
</tr>
<tr>
<td>11V</td>
<td>18</td>
<td>0.36 %</td>
</tr>
<tr>
<td>12R</td>
<td>8</td>
<td>0.16 %</td>
</tr>
<tr>
<td>12V</td>
<td>16</td>
<td>0.32 %</td>
</tr>
</tbody>
</table>

Total 5,035 100.00 % 841 100.00 %

In the present study, the 6 variable type was the most common, representing 19.64 % of all codas identified. The next most common was the 4 variable (14.78 %),
then the 7 regular type (11.88 %). These three types represent 46.3 % of all the codas in this study. In the Apple (2002) study, the most commonly occurring coda type was 8 variable representing 56.24 % of the codas identified in that study. A total of 100 codas containing 10, 11, or 12, clicks were found in the present study (representing 1.99 % of the entire repertoire), whereas Apple did not identify any codas with more than nine clicks.

Long codas were more prevalent in both studies (Figure 14); however, a Z test for proportions revealed that the percentage of long codas in this study (55.83 %) and the percentage of long codas in Apple (2002) (72.18 %) were significantly different from each other, $Z = -8.896$, $p < .001$.

![Figure 14. Comparison of the relative frequency of short codas (those containing ≤ 5 clicks) versus long codas (those containing ≥ 6 clicks in the present study and in Apple (2002). The actual number of codas identified is given in the figure.](image-url)
Coda categories (regular, variable, and plus-one) were compared with the only significant difference between the two studies emerging in the plus-one category, $Z = -2.72, p < .01$. The regular and variable categories were similar in their relative frequencies (Figure 15).

![Figure 15. Relative frequencies of coda categories for the present study and Apple (2002). Actual number of codas in each category is given.](image)

Coda classes (short regular, short variable, short plus-one, long regular, long variable, and long plus-one) were compared with only the short plus-one category exhibiting similar frequencies of occurrence in the two studies, $Z = -1.54, p > .05$. Comparisons between all other classes in this study with those in Apple (2002) revealed significant differences in their relative frequencies of occurrence (Table 8).
Table 8

Summary of the Number and Relative Frequencies of Codas Identified in the Present Study and in Apple (2002) in each of Six Coda Classes. The Z Score and p Value of the Comparison Between Studies (using Z test for proportions) are Given.

<table>
<thead>
<tr>
<th>Class</th>
<th>Present Study</th>
<th>Apple (2002)</th>
<th>Z score</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># Codas</td>
<td>%</td>
<td># Codas</td>
<td>%</td>
</tr>
<tr>
<td>Short reg</td>
<td>659</td>
<td>13.09 %</td>
<td>196</td>
<td>23.31 %</td>
</tr>
<tr>
<td>Short var</td>
<td>1,483</td>
<td>29.45 %</td>
<td>18</td>
<td>2.14 %</td>
</tr>
<tr>
<td>Short +1</td>
<td>82</td>
<td>1.63 %</td>
<td>20</td>
<td>2.38 %</td>
</tr>
<tr>
<td>Long reg</td>
<td>1,156</td>
<td>22.96 %</td>
<td>102</td>
<td>12.13 %</td>
</tr>
<tr>
<td>Long var</td>
<td>1,540</td>
<td>30.59 %</td>
<td>475</td>
<td>56.48 %</td>
</tr>
<tr>
<td>Long +1</td>
<td>115</td>
<td>2.28 %</td>
<td>30</td>
<td>3.57 %</td>
</tr>
<tr>
<td>Total</td>
<td>5,035</td>
<td>100.00 %</td>
<td>841</td>
<td>100.00 %</td>
</tr>
</tbody>
</table>

A comparison of the time of coda occurrence revealed more differences than similarities (Table 9). In Apple (2002), the majority of the identified codas occurred between 1200 – 1759 (61.59 %), whereas the codas in the present study were identified most often from 1800 – 2359 (32.83 %), the period of least occurrence in Apple’s study (2.85 %). Codas in the present study also were found frequently in the 0000 – 0659 time period (32.10 %). This time period in Apple represented the second most active period of coda production (22.95 %).
Table 9

Summary of the Number and Relative Frequencies of Codas Occurring in Each of Four Time Periods in the Present Study and in Apple (2002). The Z Score and p Value of the Comparisons Between Studies (using Z test for proportions) are Given.

<table>
<thead>
<tr>
<th>Time</th>
<th>Present Study</th>
<th>Apple (2002)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># Codas</td>
<td>%</td>
</tr>
<tr>
<td>0000-0559</td>
<td>1,616</td>
<td>32.10%</td>
</tr>
<tr>
<td>0600-1159</td>
<td>695</td>
<td>13.8%</td>
</tr>
<tr>
<td>1200-1759</td>
<td>1,071</td>
<td>21.27%</td>
</tr>
<tr>
<td>1800-2359</td>
<td>1,653</td>
<td>32.83%</td>
</tr>
<tr>
<td>Total</td>
<td>5,035</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Weilgart and Whitehead (1997). The data gathered by Weilgart and Whitehead (1997) represent several locations including the Eastern Tropical Pacific, Southwest Pacific, Southeast Pacific, and the Caribbean Sea. A total of 3,644 codas were identified with 247 of those occurring in the Caribbean Sea. The 3,644 codas were placed into 30 coda types using a protocol similar to that employed when defining the types used in the present study with the following exception: five and six-click codas were not included in Weilgart and Whitehead’s categorization of long versus short codas. They defined a short coda as having < 5 clicks and a long coda as having > 6 clicks. These five and six-click codas, as well as variable codas, were not included in further analysis by Weilgart and Whitehead. They used only short or long and regular or plus-one to describe codas.
used in their analyses of group dialects and geographical variation in sperm whale coda repertoires.

At the Caribbean Sea study site, Weilgart and Whitehead (1997) reported that only *long* codas were heard in the two days of recoding at that location. No *short* codas were heard and *regular* and *plus-one* codas were heard with approximately equal frequency.

Before a comparison of *long* versus *short* codas and *regular* versus *plus-one* codas could be made, adjustments were made to better align data from the present study and from Apple (2002). Specifically, codas containing five or six clicks were removed from the present study’s and from Apple’s data. Only codas meeting the definition of *regular* and *plus-one* codas are included in the comparison (*variable* and *one-plus* codas are excluded, Figure 16). In comparing *short* versus *long* codas, both the present study and the Weilgart and Whitehead (1997) study have more *short* than *long* codas. In contrast, the Apple study presented more *long* than *short* codas. In comparing *regular* versus *plus-one* codas, all three studies identified more *regular* than *plus-one* type codas.
Figure 16. Comparison of the relative frequencies of short, long, regular and plus-one codas in the present study, the Apple (2002) study, and in Weilgart & Whitehead (1997). Note: Five and six-click codas have been removed from the present study and from the Apple (2002) study to conform to Weilgart & Whitehead (1997) data.

Codas and Creaks

Creak Characteristics

A total of 4,376 creaks were identified in this study ranging in length from 0.08 to 102.22 s. The EARS 2 buoy (800 m) was the location with the most identified creaks (57.1 %), followed by EARS 3 (600 m) with 28.8 % and EARS 1 (1,000 m) with 14.1 % of the total creak repertoire. The difference in the number of creaks recorded at each pair of locations was significantly different, EARS 1 vs. EARS 2 $Z = -41.94$, $p < .001$; EARS 1 vs. EARS 3 $Z = -16.66$, $p < .001$; EARS 2 vs. EARS 3 $Z = 26.76$, $p < .001$ (Table 10).
Table 10

Summary of the Number of Creaks, Representative Percentage of all Creaks, Mean Durations and Standard Deviations of Creaks Recorded at Each of Three Buoy Locations.

<table>
<thead>
<tr>
<th>Buoy Location</th>
<th># of Codas</th>
<th>%</th>
<th>Mean Duration</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1 (1,000 m)</td>
<td>619</td>
<td>14.1%</td>
<td>0.92</td>
<td>0.85</td>
</tr>
<tr>
<td>E2 (800 m)</td>
<td>2,498</td>
<td>57.1%</td>
<td>0.87</td>
<td>0.78</td>
</tr>
<tr>
<td>E3 (600 m)</td>
<td>1,259</td>
<td>28.8%</td>
<td>0.91</td>
<td>2.93</td>
</tr>
<tr>
<td>Total</td>
<td>4,376</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A Kolmogorov-Smirnov test was used to assess normality of the creak duration data. Because the data were not normally distributed (Z = 22.16, p < .001), nonparametric tests of significance were used.

Overall, a significant difference in creak duration across all buoys was detected using a Kruskal-Wallis test, $\chi^2 (2, N = 4,376) = 13.9, p = .001$. Follow-up Mann Whitney $U$ tests were conducted with significant differences emerging between EARS 1 and EARS 2, $Z = -2.86, p < .01$, and between EARS 2 and EARS 3, $Z = -3.06, p < .01$.

Holm's sequential Bonferroni procedure was utilized to correct for type I error but did not affect the significance of these differences (corrected $p$ values remained < .01).

Further examination of duration characteristics was performed with all buoy locations pooled. The data set was split into two groups; creaks that were $\leq 4.0$ s in duration and those that were longer than $4.0$ s. Weigart (1990) reported that creaks occurring at the surface and associated with socializing tend to be shorter (0.1 – 4.0 s).
than those produced during foraging activities. Creaks heard from foraging whales are longer with durations typically averaging 5 – 45 s (Gordon, 1987; Miller, Johnson, & Tyack, 2004). Of the 4,376 creaks recorded, 98.9 % (4,326) were less than 4 s in duration (M = 0.81, SD = 0.51). The remaining 50 creaks had a mean of 7.75 s and a standard deviation of 13.73.

During preliminary analysis, the Julian day of each creak occurrence was noted (where Julian day 198 refers to July 17, 2001). Creaks were identified at all three buoy locations, however they were not found on each Julian day of recording (Table 11). Day 212 revealed 1792 creaks over the three buoy locations, representing 41 % of all creaks identified (67.0 % of these creaks occurred at EARS 2 at 800 m), the remainder at EARS 3 at 600 m). For EARS 2, 48 % of all codas recorded at this location were recorded on this day.
Table 11

Summary of the Number of Codas Recorded by Julian Day and EARS Buoy Location.

<table>
<thead>
<tr>
<th>Julian Day</th>
<th>EARS 1 1,000 m</th>
<th>Buoy EARS 2 800 m</th>
<th>EARS 3 600 m</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>201</td>
<td>3</td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>205</td>
<td>90</td>
<td></td>
<td></td>
<td>90</td>
</tr>
<tr>
<td>206</td>
<td>2</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>207</td>
<td>10</td>
<td>1</td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>210</td>
<td>13</td>
<td>39</td>
<td></td>
<td>52</td>
</tr>
<tr>
<td>211</td>
<td>12</td>
<td>466</td>
<td></td>
<td>478</td>
</tr>
<tr>
<td>212</td>
<td>1,199</td>
<td>593</td>
<td></td>
<td>1,792</td>
</tr>
<tr>
<td>213</td>
<td>343</td>
<td>3</td>
<td></td>
<td>346</td>
</tr>
<tr>
<td>214</td>
<td>88</td>
<td>368</td>
<td>2</td>
<td>458</td>
</tr>
<tr>
<td>215</td>
<td>1</td>
<td>77</td>
<td>18</td>
<td>96</td>
</tr>
<tr>
<td>216</td>
<td>30</td>
<td>65</td>
<td>19</td>
<td>114</td>
</tr>
<tr>
<td>217</td>
<td>71</td>
<td>43</td>
<td></td>
<td>114</td>
</tr>
<tr>
<td>218</td>
<td>1</td>
<td>8</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>219</td>
<td>10</td>
<td>30</td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>220</td>
<td>47</td>
<td>24</td>
<td>12</td>
<td>83</td>
</tr>
<tr>
<td>221</td>
<td>24</td>
<td></td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>222</td>
<td>132</td>
<td>1</td>
<td>28</td>
<td>161</td>
</tr>
<tr>
<td>223</td>
<td></td>
<td></td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>224</td>
<td>10</td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>225</td>
<td>60</td>
<td></td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>228</td>
<td>130</td>
<td>25</td>
<td>54</td>
<td>209</td>
</tr>
<tr>
<td>229</td>
<td>7</td>
<td></td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>230</td>
<td>9</td>
<td>10</td>
<td>53</td>
<td>72</td>
</tr>
<tr>
<td>231</td>
<td>120</td>
<td></td>
<td></td>
<td>120</td>
</tr>
<tr>
<td>232</td>
<td>14</td>
<td>3</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>TOTAL</td>
<td>619</td>
<td>2,498</td>
<td>1,259</td>
<td>4,376</td>
</tr>
</tbody>
</table>

A two-way contingency table analysis was performed for creaks by time quadrant and buoy location. In examining the contribution of creaks by each buoy location for each time period, a significant difference was found in creak production, $\chi^2 (6, N = 4,376) = 544.47, p < .001$ with more creaks being produced during the hours 1800–
0559; the time period which roughly corresponds to the overnight hours 6:00 pm – 5:59 am (Figures 17 & 18). The EARS 2 buoy location led in the identified number of creaks in all but the 0000 – 0559 time period with 42.9 % for the time period 0600 – 1159, 68.3 % for the time period 1200 – 1759, 68.5 % for the time period 1800 – 2359, but only 37.8 % in the 0000 – 0559 time period. Within each buoy, the proportion of creaks identified at each time quadrant varied with more creaks recorded at the time period 0000 – 0559 and 1800 – 2359 at all buoy locations (Figure 19).

![Figure 17. Relative frequency of creaks per time quadrant identified at each buoy location. Actual number of creaks is provided.](image-url)
Figure 18. Frequency of creaks occurring during each time period from all EARS locations combined.
A variety of creak types were identified in the recordings from all buoy locations. Creaks were assigned to a “type” category if their structure differed from the standard definition of a creak. Creaks typically have a pattern of very closely spaced clicks, often with the click rate accelerating over the course of the creak because a whale is likely homing in on a prey item. Some creaks in this study were found to have a different structure, often containing more widely-spaced clicks (more similar to those found in codas) either before, after, or both before and after the body of the creak.

Beyond the “typical” creak, 15 creak types were identified (plus 1, plus 2, plus 3, plus 4, plus 5, plus 6, plus 7, 1 plus, 2 plus, 3 plus, 4 plus, 5 plus, 6 plus, 10 plus, and plus creak plus). The “k plus” creaks (where k represents a number of coda-like clicks) are characterized by k clicks preceding a typical creak structure (Figure 20).
Figure 20. Spectrograph image showing two 2-plus type creaks (between solid black arrows). Two typical creaks are also present (between dashed arrows). From E3 (600 m) buoy recording file 08652121.

Similarly, the “plus k” types end with k coda-like clicks. The “plus creak plus” type describes a creak where the typical creak structure is surrounded (immediately preceding and subsequent to the creak) by coda-like clicks. This creak type was rare enough so that all creaks that fit this description (without regard to the specific number of clicks before or after) were placed into this category (N = 27). Overall, 801 creaks fitting one of the above-described atypical click types were identified representing 18.3% of all creaks (Table 12).
Table 12

Type and Frequency of Creaks That Did Not Match the Description of “Typical” Creaks, the Representative Percentage of Each Creak Type, and the Overall Percentage Represented by Each Creak Type When Compared to the Total Number of Creaks

<table>
<thead>
<tr>
<th>Creak Type</th>
<th>Frequency</th>
<th>% of “typed” Creaks</th>
<th>% of all Creaks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plus 1</td>
<td>11</td>
<td>1.4 %</td>
<td>0.3 %</td>
</tr>
<tr>
<td>Plus 2</td>
<td>17</td>
<td>2.1 %</td>
<td>0.4 %</td>
</tr>
<tr>
<td>Plus 3</td>
<td>15</td>
<td>1.9 %</td>
<td>0.3 %</td>
</tr>
<tr>
<td>Plus 4</td>
<td>6</td>
<td>0.7 %</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Plus 5</td>
<td>4</td>
<td>0.5 %</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Plus 6</td>
<td>7</td>
<td>0.9 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Plus 7</td>
<td>1</td>
<td>0.1 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td>1 Plus</td>
<td>27</td>
<td>3.4 %</td>
<td>0.6 %</td>
</tr>
<tr>
<td>2 Plus</td>
<td>271</td>
<td>33.8 %</td>
<td>6.2 %</td>
</tr>
<tr>
<td>3 Plus</td>
<td>373</td>
<td>46.6 %</td>
<td>8.5 %</td>
</tr>
<tr>
<td>4 Plus</td>
<td>27</td>
<td>3.4 %</td>
<td>0.6 %</td>
</tr>
<tr>
<td>5 Plus</td>
<td>7</td>
<td>0.9 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>6 Plus</td>
<td>6</td>
<td>0.7 %</td>
<td>0.1 %</td>
</tr>
<tr>
<td>10 Plus</td>
<td>1</td>
<td>0.1 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td>8 Plus</td>
<td>1</td>
<td>0.1 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td>Plus creak</td>
<td>27</td>
<td>3.4 %</td>
<td>0.6 %</td>
</tr>
<tr>
<td>TOTAL</td>
<td>801</td>
<td>100.0 %</td>
<td>18.3 %</td>
</tr>
</tbody>
</table>
From those creaks recorded at the EARS 1 buoy location (1,000 m), 118 of the 619 creaks (19.1%) fell into one of the creak types. From EARS 2 (800 m), 397 of the 2,498 (15.9%) were of a form consistent with a type listed above, and from EARS 3 (600 m), 286 (22.8%) of the 1,259 identified creaks belonged in one of these type categories (Table 13). To determine whether a difference existed between buoy locations in the percentage of creaks that were atypical, Z tests for proportions were performed. A significant difference was found between EARS 2 and EARS 3, Z = -5.12, p < .001. The difference in the proportion of creaks that were atypical between EARS 1 and EARS 2, Z = 1.42, p > .05 and between EARS 1 and EARS 3, Z = -2.18, p < .05 however, was not significant. Overall, the average duration of the atypical creaks was 0.91 s (SD 0.30).
Table 13

*Summary of the Number of Creaks in each Creak Type Recorded at Each Buoy Location.*

<table>
<thead>
<tr>
<th>Creak Type</th>
<th>Buoy EARS 1 1,000 m</th>
<th>Buoy EARS 2 800 m</th>
<th>Buoy EARS 3 600 m</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical creak</td>
<td>501</td>
<td>2101</td>
<td>973</td>
<td>3575</td>
</tr>
<tr>
<td>Plus 1</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>Plus 2</td>
<td>4</td>
<td>7</td>
<td>6</td>
<td>17</td>
</tr>
<tr>
<td>Plus 3</td>
<td>7</td>
<td>5</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Plus 4</td>
<td>5</td>
<td>1</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Plus 5</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Plus 6</td>
<td>4</td>
<td>0</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Plus 7</td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1 Plus</td>
<td>6</td>
<td>17</td>
<td>4</td>
<td>27</td>
</tr>
<tr>
<td>2 Plus</td>
<td>42</td>
<td>134</td>
<td>95</td>
<td>271</td>
</tr>
<tr>
<td>3 Plus</td>
<td>29</td>
<td>197</td>
<td>147</td>
<td>373</td>
</tr>
<tr>
<td>4 Plus</td>
<td>3</td>
<td>15</td>
<td>9</td>
<td>27</td>
</tr>
<tr>
<td>5 Plus</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>6 Plus</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>8 Plus</td>
<td>1</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>10 Plus</td>
<td>1</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Plus creak Plus</td>
<td>8</td>
<td>13</td>
<td>6</td>
<td>27</td>
</tr>
<tr>
<td>TOTAL</td>
<td>619</td>
<td>2,498</td>
<td>1,259</td>
<td>4,376</td>
</tr>
</tbody>
</table>

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Co-occurrence of Codas and Creaks

The co-occurrence of creaks and codas was examined to determine how often codas were heard when creaks were also present. Overall, 81.5% (3,566 of 4,376) of all creaks occurred in the presence of a coda. A two-way contingency table analysis between EARS location (EARS 1 – 1,000 m, EARS 2 – 800 m, and EARS 3 – 600 m) and whether or not a coda was present was conducted and revealed a significant difference between buoys, $\chi^2 (2, N = 4,376) = 194.22, p < .001$ (Figure 21).

![Relative Frequency of Creaks per Buoy Location](image)

Figure 21. Relative frequency of creaks per buoy location that were and were not identified in the presence of a coda.
Overall, the EARS 2 (800 m) location revealed the greatest number of creaks (2,498) with only 595 of those occurring in the absence of codas. EARS 3 (600 m) recordings contained 1,259 creaks with only 71 occurring in the absence of codas, and EARS 1 (1,000 m) contained 619 creaks, with 144 occurring in the absence of codas.

Each buoy location was examined individually for a difference in the duration of creaks in the presence or absence of a coda (Table 14). Mann-Whitney U tests were conducted and revealed that only the EARS 3 (600 m) recordings contained creaks of significantly different lengths when codas were present than when codas were not \( Z = -2.85, p < .01 \).
Table 14

*Creak Duration Mean and Standard Deviation in the Presence or Absence of Codas at Each EARS Buoy Location.*

<table>
<thead>
<tr>
<th>Buoy Location</th>
<th>Codas Present?</th>
<th>N</th>
<th>Mean (in s)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1 1,000 m</td>
<td>Yes</td>
<td>475</td>
<td>0.976</td>
<td>0.931</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>144</td>
<td>0.742</td>
<td>0.420</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>619</td>
<td>0.922</td>
<td>0.846</td>
</tr>
<tr>
<td>E2 800 m</td>
<td>Yes</td>
<td>1,903</td>
<td>0.856</td>
<td>0.742</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>595</td>
<td>0.921</td>
<td>0.880</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>2,498</td>
<td>0.872</td>
<td>0.778</td>
</tr>
<tr>
<td>E3 600 m</td>
<td>Yes</td>
<td>1,188</td>
<td>0.885</td>
<td>2.969</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>71</td>
<td>1.386</td>
<td>2.039</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>1,259</td>
<td>0.914</td>
<td>2.926</td>
</tr>
<tr>
<td>TOTAL</td>
<td>Yes</td>
<td>3,566</td>
<td>0.882</td>
<td>1.829</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>810</td>
<td>0.930</td>
<td>0.992</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>4,376</td>
<td>0.868</td>
<td>0.750</td>
</tr>
</tbody>
</table>

The co-occurrence of creaks and codas was further explored by using time of day as a grouping variable in a contingency table analysis. There was an overall significant
difference in the number of creaks produced in the presence of codas when time of day was a factor, $\chi^2 (3, N = 4,376) = 66.74, p < .001$ (Figure 22). When each buoy location was examined individually, a significant difference in creak production by time of day was identified at the E1 (1,000 m) and E2 (800 m) locations; E1 $\chi^2 (3, N = 619) = 122.02, p < .001$, E2 $\chi^2 (3, N = 2,498) = 77.35, p < .001$. The difference in the number of creaks produced in the presence or absence of codas by time of day did not significantly differ at the E3 (600 m) location; E3 $\chi^2 (3, N = 1,259) = 1.17, p > .05$ (Figures 23 - 25).

![All EARS Locations](image)

*Figure 22.* Frequency of all creaks that occurred during each time period at all EARS buoy locations when codas were present and when codas were absent.
**Figure 23.** Frequency of creaks occurring during each time period at the EARS 1 buoy location when codas were present and when codas were absent.

**Figure 24.** Frequency of creaks occurring during each time period at the EARS 2 buoy location when codas were present and when codas were absent.
Figure 25. Frequency of creaks occurring during each time period at the EARS 3 buoy location when codas were present and when codas were absent.

Further analyses involving the co-occurrence of creaks and codas were performed. An analysis of where the codas occurred in the file compared to the creaks revealed that overall, a coda was as likely to occur before the creak as after the creak within the same file, $Z = 1.60$, $p > .05$ (Z test for proportions was used in this analysis). This also was true when each EARS location was examined individually. Of the 619 creaks identified at E1 (1,000 m), 63.8% had a coda identified before it in the file and 66.2% of those creaks had a coda identified after. At E2 (800 m) 53.8% of creaks identified were associated with a coda occurring prior to the creak and 56.0% were associated with a coda occurring after the creak. Similarly, at E3 (600 m) 80.5% of creaks were associated with a coda occurring prior and 80.7% were associated with a coda occurring after the creak within the same file.
The distances between the onset of the creak and the onset of the preceding and following codas, varied by buoy (Table 15). The mean time between creaks and preceding codas was significantly different between EARS locations $\chi^2 (2, N = 2,757) = 115.14, p < .001$. Similarly, the mean time between creaks and the codas that followed those creaks in the same file was also significantly different between buoy locations $\chi^2 (2, N = 2,825) = 154.12, p < .001$. The time between creaks and codas at E2 (800 m) tended to be the longest for both preceding and following codas, while E1 (1,000 m) revealed the shortest elapsed time between these two types of vocalizations.

Table 15

Mean Amount of Time Between a Creak and the Coda Occurring Closest in Proximity Before and After that Creak Within the Same File.

<table>
<thead>
<tr>
<th>Buoy</th>
<th>N</th>
<th>Coda Before</th>
<th>Coda After</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean (in s)</td>
<td>SD</td>
</tr>
<tr>
<td>EARS 1</td>
<td>1,000 m</td>
<td>395</td>
<td>22.59</td>
</tr>
<tr>
<td></td>
<td>800 m</td>
<td>1,349</td>
<td>44.35</td>
</tr>
<tr>
<td></td>
<td>600 m</td>
<td>1,013</td>
<td>32.40</td>
</tr>
</tbody>
</table>
Further examination of the codas that occurred prior to and after a creak was conducted. Specifically, the number of clicks that these codas contained (the coda group) was explored (Figures 26 & 27). In examining codas occurring prior to a creak, the 6-click group was more common at the EARS 1 (1,000 m) and EARS 2 (800 m) locations with 127 and 426 occurrences respectively. The EARS 3 (600 m) location revealed more codas containing 4 clicks (347). The same pattern emerged when examining the codas occurring after a creak. The E1 and E2 locations revealed more 6-click codas (131 and 516 respectively) while the E3 location contained more 4-click codas (335).

Figure 26. Frequency of occurrence of coda group (number of clicks in the coda) that the codas occurring closest in proximity prior to a creak contained by EARS buoy location.
Figure 27. Frequency of occurrence of coda group (number of clicks in the coda) that the codas occurring closest in proximity after a creak contained by EARS buoy location.

The types of creaks produced in the presence of codas varied, with all creak types represented when codas were present. However, not all creak types were represented when creaks occurred in the absence of a coda (Table 16). The most commonly seen patterns of atypical creaks (both when codas were present as well as when they were absent) were the 2 plus and 3 plus types (together representing 80.4 % of all atypical creaks). The 2 plus and 3 plus types were represented at all three buoy locations. A total of 271 2 plus type creaks was recorded: 42 from E1 (1,000 m), 134 from E2 (800 m), and 95 from E3 (600 m). At E1, 14.3 % (6) of those creaks were identified in the presence of codas. At E2, 67.9 % (91) were identified in the presence of codas, and at E3, 95.8 % (91) were recorded in the presence of a coda. A total of 373 3 plus type creaks was identified: 29 from E1, 197 from E2, and 147 from the E3 buoy location. At E1, 55.2 %
(16) of the 3 plus type creaks were recorded in the presence of a coda. At E2, 66.0 %
(130) were identified in the presence of a coda, and at E3, 98.0 % (144) co-occurred with
at least one coda.
Table 16

_Creak Types Produced and Their Frequencies When Codas Were Present and When Codas Were Absent. Percentage of all Creaks that Each Creak Type Represents is also Provided_

<table>
<thead>
<tr>
<th>Creak Type</th>
<th>Codas Present</th>
<th>Coda Absent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>% of all creaks</td>
</tr>
<tr>
<td>Typical</td>
<td>2,944</td>
<td>67.3 %</td>
</tr>
<tr>
<td>Plus 1</td>
<td>10</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Plus 2</td>
<td>17</td>
<td>0.4 %</td>
</tr>
<tr>
<td>Plus 3</td>
<td>14</td>
<td>0.3 %</td>
</tr>
<tr>
<td>Plus 4</td>
<td>6</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Plus 5</td>
<td>4</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Plus 6</td>
<td>7</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Plus 7</td>
<td>1</td>
<td>0.0 %</td>
</tr>
<tr>
<td>1 Plus</td>
<td>18</td>
<td>0.4 %</td>
</tr>
<tr>
<td>2 Plus</td>
<td>188</td>
<td>4.3 %</td>
</tr>
<tr>
<td>3 Plus</td>
<td>290</td>
<td>6.6 %</td>
</tr>
<tr>
<td>4 Plus</td>
<td>26</td>
<td>0.6 %</td>
</tr>
<tr>
<td>5 Plus</td>
<td>7</td>
<td>0.2 %</td>
</tr>
<tr>
<td>6 Plus</td>
<td>6</td>
<td>0.1 %</td>
</tr>
<tr>
<td>8 Plus</td>
<td>1</td>
<td>0.0 %</td>
</tr>
<tr>
<td>10 Plus</td>
<td>1</td>
<td>0.0 %</td>
</tr>
<tr>
<td>Plus cr Plus</td>
<td>26</td>
<td>0.6 %</td>
</tr>
<tr>
<td>TOTAL</td>
<td>3,566</td>
<td>81.5 %</td>
</tr>
</tbody>
</table>

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The EARS buoy recordings were examined to determine if a difference existed in the proportion of typical creaks found when codas were present and when they were absent at and between each buoy location (Figure 28). At E1 (1,000 m), 86.1% (409 of 475) of the creaks identified when codas were present had a typical structure, while 63.9% (92 of 144) of the creaks identified when codas were absent were typical. At E2 (800 m), 85.4% (1,626 of 1,903) of the creaks in the “coda present” category and 79.8% (475 of 595) of the “coda absent” creaks were of the typical variety. At E3 (600 m), 76.5% (909 of 1,188) of the creaks found when codas were present and 90.1% (64 of 71) of creaks found in the absence of codas were typical. Z tests for proportions conducted on each EARS location individually revealed significant differences in the

![Figure 28. Relative frequency of typical and atypical creaks that occurred at each EARS buoy location when codas were present and when codas were absent.](image-url)
occurrence of typical creaks when codas were present versus when codas were absent at all three locations: E1 (1,000 m) $Z = 5.95, p < .001$, E2 (800 m) $Z = 3.27, p < .01$, E3 (600 m) $Z = -2.66, p < .01$.

Comparisons between locations (EARS 1 vs. EARS 2, EARS 1 vs. EARS 3, and EARS 2 vs. EARS 3) were made to determine if there was a difference in the number of typical creaks found: 1) when codas were present, and 2) when codas were absent (Table 17). Z tests for proportions were used in the comparison and revealed more differences than similarities; only the difference in typical codas between EARS 1 and EARS 2 when codas were present was not significant, $Z = 0.37, p > .05$.

Table 17

<table>
<thead>
<tr>
<th>Buoy Location</th>
<th>Coda Present</th>
<th>Coda Absent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Z Score</td>
<td>p value</td>
</tr>
<tr>
<td>E1 vs. E2</td>
<td>0.37</td>
<td>&gt;.05</td>
</tr>
<tr>
<td>E1 vs. E3</td>
<td>4.36</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>E2 vs. E3</td>
<td>6.29</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>
CHAPTER V
DISCUSSION

Codas

Classification and Repertoire Identification

The present study identified and classified 5,035 codas recorded at three EARS buoy locations in the Northern Gulf of Mexico. From these analyses, 34 coda types were identified based on the number of clicks the codas contained and the structure or pattern of those clicks. Type 6V was the most commonly occurring coda type, representing just over 19% of all codas. There were more long codas than short ones and variable codas were more prevalent than the regular, plus-one or one-plus forms. Because of the classification protocol of placing patterns with less than 50 codas into the variable category, the large number of codas in the variable category could be expected.

The identification of the coda repertoire from sperm whales in a given area can provide information not only about vocal behavior, but also about group structure and group affiliation. The present study recorded a large number of codas over the course of the study period. Because codas from known breeding grounds are often produced by socializing females (Goold, 1999; Gordon et al., 1992; Marcoux et al., 2006), and this study area is known to be inhabited by a mixed group of mature females and immatures (Watwood, et al., 2006; Würsig et al., 1999), it is likely that there were mature females in or passing through the area for much of the study period.

Information in the coda repertoire of sperm whales can also be used in determining group affiliation. Social units of sperm whales can be assigned to "vocal
clans" based on the production frequency of certain coda types and photo-identification records (Rendell & Whitehead, 2003). For example, a “regular clan” is defined by the production of codas with regularly spaced intervals, whereas a “plus-one clan” produces more codas with a longer interval between the last two clicks in the coda. Rendell and Whitehead found that sperm whale units (consisting of ~12 individuals and stable over decades) consistently form groups (temporary collections of two or more units that associate for 7 – 10 days) with other units from the same clan. The clans they identified were primarily in the South Pacific and little mixing would be expected with the sperm whales in the Northern Gulf of Mexico. However, they also identified one clan in the Caribbean (+2 clan) that predominately used codas with a 5 + 2 or a 6 + 1 + 1 structure. Although the codas in the present study are not representative of this clan, future research combining photo-identification information and genetic analyses with coda repertoire information could define any clans that might inhabit this region.

Location Analyses

Codas were recorded at all three EARS buoy locations. Overall, 1,106 codas were identified at the EARS 1 (1,000 m) location (located the farthest out into the Gulf), 1,950 at EARS 2 (800 m), and 1,979 at the EARS 3 (600 m) location (located closest to shore and approximately 25 km from EARS 1). The depth of the hydrophone should not have been a factor, as clicks produced at the surface would be recorded on even the deepest hydrophone (A. Wright, pers. comm., 2007). Furthermore, it is not likely that codas were recorded on more than one hydrophone as the average range that a coda
propagates is approximately 2 km (Madsen, 2002; Whitehead, 2003) and the distance between the two buoys situated closest in proximity was approximately 7 km.

Codas are most often produced when whales are socializing at the surface (average rate of 4.04 codas per minute) and to a lesser extent during foraging dives (rate of 0.75 codas per minute) (Whitehead & Weilgart, 1991). In the present study, the two hydrophones closest to shore (at 600 and 800 m) recorded the most codas and the hydrophone the farthest out into the Gulf, in the deepest water, recorded the fewest codas. These findings could support the Madsen (2002) and Whitehead (2003) statistics on the relative frequency of coda production when socializing versus when foraging if the whales were primarily engaged in foraging activity in the deeper waters near the EARS 1 (1,000 m) buoy.

The position of the EARS buoys at the edge of the continental shelf could have been another factor in the number of codas identified at each location. In a study comparing two types of foraging environments (continental slope versus an oceanic island environment), Amano, Aoki, Yoshioka, and Mori (2005) found that sperm whales change their foraging behavior in different settings. Specifically, the diving pattern at the continental shelf location stayed consistent for day versus night, whereas off the oceanic islands, daytime dives were typically deeper than nighttime dives. Although this diel pattern does not fit with the present study’s results (see Time Analyses) perhaps the whales in this region of the world follow a different pattern. Sperm whales in this study could have moved toward the deeper buoy (E1 at 1,000 m) down the continental shelf to feed during the daytime hours (specifically 0600 - 1159 when fewer codas were reported).
Alternatively, there could have been fewer whales in the proximity of the EARS 1 buoy thereby reducing the number of vocalizations recorded. Our lack of observational data during bouts of vocal activity makes assigning codas to a particular behavior impossible.

**Time Analyses**

Higher numbers of codas were heard in the periods 0000 – 0559, 1200 – 1759, and 1800 – 2359. During the first time period of the 24-hour day, a total of 1,616 codas were identified. The last period contained 1,653 codas, and the third period of the 24-hour day revealed 1,071 codas. The second period of the day contained the fewest number with only 695 codas identified. Whitehead and Weilgart (1991) report that off the Galápagos Islands, the bouts of socializing at the surface each averaged 2 – 3 hours, beginning at around 0800 and peaking at about 1600. Less frequently, foraging was also seen in the afternoon with socializing occurring primarily in the morning hours. If increased coda production is an estimator of social activity, the whales in the present study are different from those in the Galápagos in the timing of peak social activity. The whales in the Northern Gulf of Mexico seem to prefer the nighttime hours to socialize.

The first and last periods of the day encompass sunrise and sunset in the present study; sunrise occurred between 0511 and 0534 with sunset occurring between 1902 and 1831. The reduction in coda production during the second period of the day (0600 – 1159) could be an indication that foraging had occurred just prior and whales were engaged in periods of reduced vocalizations after completing foraging dives. Several species of squid that have been found in sperm whale stomachs use light levels associated
with daybreak to begin their vertical migration to the surface (Clarke, Martin, & Pascoe, 1993; Martin & Clarke, 1986). In the present study, daybreak occurred just prior to the onset of the period of reduced coda production, potentially corresponding with typical après dive behavior. Whales could have been involved in foraging activity associated with the ascending squid at daybreak, then could have participated in more rest during the period 0600 – 1159. Norris, Evans, Benson, & Sparks (1996) reported a similar pattern of behavior, with deep dives followed by periods of silence at the surface.

Apple (2002) reported a significant difference in the timing of coda production; specifically, many more codas (519) during the period 1200 – 1759 and many fewer codas (24) during the period 1800 – 2359. Apple reported 193 codas identified between 0000 – 0559 and 106 codas during the time period 0600 – 1159. As in the present study, the Apple study reported a reduction in coda production during the second time period (0600 – 1159).

The increased variability in coda production over the course of a 24-hour period in the present study as compared to the higher concentration of coda production during one time period in the Apple (2002) study could be explained by location. The EARS buoys were moored in an area with frequent boat disturbance, which could have an impact on the already variable timing of socializing and foraging behavior (see Whitehead, 2003).

Repertoire Comparison

The protocols used in the present study closely resembled those utilized by Apple (2002). Minor modifications were made to conduct accurate comparisons because of the
presence of one coda category in the present study that was not identified in the Apple study (see methods section). Both studies were conducted in the Northern Gulf of Mexico, but Apple gathered data with towed hydrophone arrays whereas the present study relied on stationary bottom-moored hydrophones. The Apple study site was split with first-year data collected in an area spanning the Texas-Mexico border to the Florida-Alabama border and the 100 m to 2,000 m isobaths. The second year’s data were gathered in the north-central Gulf of Mexico from just west of New Orleans to the mid-panhandle region of Florida and from just offshore to deep into the mid-Gulf. Overall, both Apple study sites overlap the location of the present study’s stationary recording sites.

Apple (2002) identified 841 codas representing 17 coda types. The present study identified 5,035 codas representing 27 types (after adjustments for comparison). The Apple study did not identify any codas with greater than nine clicks. Coda types in the present study with more than nine clicks represent only 4.81 % of the coda repertoire. The absence of these longer codas in the Apple dataset could be related to the overall scarcity of production of these longer coda types by whales in this region.

The most common coda type identified by Apple (2002) was the 8 variable coda (56.24 %). The most prevalent type in the present study was the 6 variable coda (19.64 %). The general trend indicated that long codas were more prevalent in both study sets than short codas, however a significant difference between studies existed. Greater similarity was seen when examining coda categories across the data sets. The regular and variable categories were similar in their representative percentage of the overall repertoires. The plus-one category was the only category determined to be significantly
different between the two studies. Similarly, when comparing the number of codas in each coda class, the only class that differed significantly between the two studies was the short plus-one class.

Despite the difference in the most prevalent coda type identified, there is a great deal of similarity between these two data sets. The similarity in coda repertoires supports the idea that a resident population of sperm whales inhabits this region.

A descriptive comparison was also executed between the present study’s dataset and the dataset obtained in Weilgart and Whitehead’s (1993, 1997) studies in the Eastern Tropical Pacific, Southwest Pacific, Southeast Pacific, and the Caribbean Sea. They recognized 30 coda types when data from all sites were pooled. A total of 247 codas from the Caribbean were identified, but their coda types were not separated from the types identified at the other locations. With all sites pooled, 3 regular was the most common type of coda found.

A three-way comparison with the present study, Apple (2002), and the Weilgart & Whitehead (1997) study, reveals that the regular category is more common than the plus-one category (reminder: the variable category was not included in analyses in Weilgart & Whitehead so was dropped from the present study and from Apple’s study for the sake of consistency). There was more similarity in long versus short codas between the present study and Weilgart and Whitehead with both exhibiting a greater number of short codas. The Apple study contained far more long than short codas. However, the removal of codas with five or six clicks to better align the present study and Apple with Weilgart and Whitehead’s study may have had an impact on these distributions. Overall, with five and six-click codas removed, the present study’s total coda repertoire was reduced by 40.00%
(including the most prevalent type: 6 variable), while the Apple study's repertoire was reduced by 19.02%, but still contained the type most commonly seen: 8 variable.

A cursory global comparison between coda repertoires identified in various parts of the world (NGoM, Caribbean, S. Pacific, and the Mediterranean) reveals more differences than similarities between the Mediterranean and the other locations (Table 18). Table 18 depicts the obvious differences in the most commonly occurring coda type between the Mediterranean and the other study locations.
Table 18

*Frequency of Most Common Coda Type Found in Present Study and in Other Studies Around the World. The Studies are Listed in Order of Geographic Proximity to the Present Study.*

<table>
<thead>
<tr>
<th>Study</th>
<th>Area</th>
<th>Most Common Coda Type</th>
<th>Relative Frequency of Most Common Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paulos (2007)</td>
<td>Northern Gulf of Mexico</td>
<td>6V</td>
<td>19.1 %</td>
</tr>
<tr>
<td>Apple (2002)</td>
<td>Northern Gulf of Mexico</td>
<td>8V</td>
<td>56.2 %</td>
</tr>
<tr>
<td>Weilgart &amp; Whitehead (1997)</td>
<td>Galápagos, S. Pacific, Caribbean</td>
<td>3R</td>
<td>17.2 %</td>
</tr>
<tr>
<td>Weilgart &amp; Whitehead (1993)</td>
<td>Galápagos</td>
<td>5R</td>
<td>17.4 %</td>
</tr>
<tr>
<td>Drouot, Goold, &amp; Gannier (2004)</td>
<td>SW Basin, Ionian, &amp; Tyrrenian Seas in the Mediterranean</td>
<td>3 + 1</td>
<td>31.8 %</td>
</tr>
<tr>
<td>Drouot &amp; Gannier (1999)</td>
<td>Ionian Sea in the Mediterranean</td>
<td>3 + 1</td>
<td>76.1 %</td>
</tr>
<tr>
<td>Drouot &amp; Gannier (1999)</td>
<td>Tyrrenian Sea in the Mediterranean</td>
<td>3 + 1</td>
<td>33.3 %</td>
</tr>
<tr>
<td>Pavan, et al. (2000)</td>
<td>Mediterranean Sea</td>
<td>3 + 1</td>
<td>97.1 %</td>
</tr>
</tbody>
</table>

Around the Mediterranean Sea, Drouot and Gannier (1999) identified 86 codas of six distinct types (three in the Ionian Sea, three in the Tyrrenian Sea). These codas all
contained either three, four, five, or seven clicks with variable spacing, however the three coda patterns from the Ionian Sea all started with 3 rapid clicks. In a later study, Drouot, Goold, and Gannier (2004) reported a larger study in the same region in which 751 codas were identified. The codas ranged in length from three to 11 clicks with 4-click codas being the most common. The majority of the codas in this study also contained the “root” of three rapid clicks followed by more widely-spaced clicks. In another area of the Mediterranean, specifically the Ligurian Sea, Pavan and colleagues (2000) recorded 138 codas, 134 of which were all of the same type (3 + 1).

In Drouot and Gannier (1999), no regular codas were found and only one plus-one type was identified. In a later study, Drouot and colleagues (2004) revealed a more varied coda repertoire which included some regular coda types (overall representing 7.5% of the total dataset). However, this larger dataset was also consistent in revealing a large number of codas with the three-click root followed by the addition of more widely-spaced clicks. In the Pavan et al. (2000) study, nearly all of the codas recorded were of the type 3 + 1.

In the present study, the pattern defined by a three-click root followed by widely-spaced clicks was not identified. The 3 + 1 type was identified, however only 17 of the 5,035 (0.34 %) codas were of this type. Similarly, Apple (2002) also recorded codas of this type, but only 6 of the 841 (0.71 %) identified codas fit this classification. The small sample size (N = 138) of the Pavan et al. study might have hampered efforts to identify a complete repertoire.

The similarities seen between the present study and Apple (2000) and between the studies conducted in the Mediterranean combined with the differences identified between
coda repertoires from the two locations (Gulf of Mexico and Mediterranean Sea) lend further support to the concept that group-specific dialects and geographical variation are present in sperm whale coda repertoires (Rendell & Whitehead, 2003; Rendell & Whitehead, 2005; Weilgart & Whitehead, 1997).

Codas and Creaks

Creak Characteristics

The 4,376 creaks identified in this study were recorded at all three EARS buoy locations. The number of creaks recorded at each location was significantly different. The EARS 2 buoy (800 m) was the site of over 57% of all creak recordings. This number was greatly influenced by the recording of 1,199 creaks on Julian day 212. After removing these creaks from the analysis, the difference between EARS 2 and EARS 3 (600 m) was no longer significant. As creaks are most often associated with homing echolocation while foraging (Miller, Johnson, & Tyack, 2004; Whitehead, 2003), this frequency inflation might have been related to a productive period of foraging activity. However, the duration of the creaks produced on Julian day 212 and recorded at the EARS 2 and EARS 3 locations had a mean duration of 0.75 s (SD = 0.409) which more closely aligns with the definition of creaks used in bouts of socialization.

Overall, 98.9% of the creaks recorded in this study had durations less than 4.0 s, an indication that these were socialization creaks and not foraging creaks. The interclick interval is another measure used to distinguish the two types of creaks. The creaks heard in the presence of socializing whales generally have longer interclick intervals (50 – 100 ms) than the creaks heard while whales are foraging (5 – 40 ms) (Gordon, 1987; Miller,
Johnson, & Tyack, 2004). In the present study, measurements of the interclick intervals of creaks were unavailable because of the low sampling rate of the recordings. The fine detail of the click structure within the creaks was sacrificed to ensure a longer recording period. Therefore, the present study must rely solely on creak duration as an indicator of potential context.

Julian day 212 (July 31) was the most prolific 24-hour period of creak production at the EARS 2 (800 m) and EARS 3 (600 m) buoy locations. In contrast, no creaks were recorded at EARS 1 (1,000 m) from Julian day 211 through day 213. In an analysis of the effects of Tropical Storm Barry (August 2 – August 6, 2001) on the click production of sperm whales, Wright (2003) reported the highest mean click rate for the EARS 2 and EARS 3 locations occurred on Julian day 212. Julian day 212 would have been several days prior to the actual onset of the storm. At its closest point, on August 4th, the storm was located approximately 172 km from the EARS buoy locations (Wright, 2003). The present study’s findings would support Wright’s postulation that whales moved toward shore, away from EARS 1, during this period of time, perhaps in an attempt to avoid the storm. This would explain the lack of creaks at EARS 1 and the increase in creaks heard closer to shore at EARS 2 and EARS 3.

Creaks were produced with varying frequency throughout the 24-hour day at all three EARS buoy locations. The EARS 1 location showed a marked difference in production with very few creaks being produced between 1200 and 1759. The pattern was similar at the other two EARS locations where more creaks were produced in two sequential time quadrants that span the hours 1800 – 0559. The first and last periods of the day encompass sunrise and sunset in the present study; sunrise occurred between
0511 and 0534 with sunset occurring between 1902 and 1831. In the Galápagos, Whitehead and Weilgart (1991) report that large numbers of whales would "fluke up" and begin deep dives just as the sun set. However, if the duration of these creaks is an indicator of their function, then the differences in creak production by time quadrant cannot be attributed to foraging activity due to their short durations. In this population of sperm whales, the peak period of socialization seems to occur during the nighttime hours.

All of the creaks in this study did not fit the description of a "typical" creak: a pattern of closely spaced clicks that may sound like the creak of a rusty hinge (Gordon, 1987; Goold, 1999, Weilgart, 1990; Whitehead, 2003). Goold and Jones (1995) and Miller and colleagues (2004) report and that these typical creaks are associated with foraging activity and appear to be analogous to the "terminal buzzes" produced by other echolocating species such as the Daubenton's bat, *Myotis daubentonii* (Britton & Jones, 1999), or other odontocetes (Au, 1993, Dudzinski, 1996; Johnson, Madsen, Zimmer, Aguilar de Soto, & Tyack, 2004; Kastelein, Nieuwstraten, & Verboom, 1995; Miller, Pristed, Möhl, & Surlykke, 1995). Of all 4,376 creaks recorded in this study, a total of 795 creaks contained preceding or ending coda-like clicks. The number of coda-like clicks situated prior to the body of the creak varied from one to six (one creak was identified with 10 coda-like clicks) with two being the most common (N = 15). The number of coda-like clicks occurring after the body of the creak in these atypical creaks varied from one to seven with two (N = 271) and 3 (N = 374) being the most common. Some creaks exhibited coda-like creaks both before and after the body of the creak (N = 27). These creaks with coda-like properties could be more closely related to the "coda-creaks" (Weilgart, 1990, p. 85) or the "rapid clicks" or "chirrups" (Goold, 1999; Gordon,
1987, p. 213) identified in other studies. Based on the average duration of these atypical creaks vocalizations (0.92 s), they would fall into the category of socializing creaks (Weilgart, 1990).

**Co-occurrence of Codas and Creaks**

Codas, and to a lesser extent creaks, have been reported to be involved in communication between sperm whales (for review, see Whitehead, 2003). The present study examined the relationship between these two potentially communicative vocalizations and discovered that 81.5% of all creaks produced, occurred in the presence of a coda (within the same file as a coda). The EARS 3 buoy site, (closest to shore and moored in 600 m of water) was the only site that exhibited a significant variance in creak duration when codas were absent versus when codas were present. Perhaps, the creaks in the absence of codas at this particular location were associated with foraging activity. The mean duration of these creaks was still less than the 5 – 45 s reported as an average duration for foraging associated creaks (Gordon, 1987; Miller, Johnson, & Tyack, 2004); however, it was still significantly longer than the durations of other creaks in this study.

The co-occurrence of codas and creaks was observed at all EARS buoy locations and during all four time periods with varying frequencies. During the overnight hours (corresponding to 1800 through 0559) many more codas and creaks were identified. This finding further supports the theory that whales in this region might be engaged in socialization activity during the nighttime hours.

When examining where a coda was most likely to occur in relation to a creak within the same file, it was determined that it was equally as likely for the coda to occur
before the onset of the creak as after. This was true for all three buoy locations thereby suggesting that perhaps it is not so important whether the coda or the creak come first, but that they occur in proximity of one another that is key. However, due to the lack of behavioral data, it should be noted that we do not have any information regarding the identification of the vocalizing whales, so do not know whether the same animal is producing both types of vocalizations or if more than one whale is involving in producing only the codas or the creaks.

The distance between the two types of vocalizations varied by buoy and by whether or not the coda occurred before or after the creak. The longest gap between types of vocalizations occurred at the EARS 2 location (800 m) for both preceding and following codas. This is also the location with the greatest number of codas and creaks but density of vocalizations was not likely to be a factor given these results. One possible explanation might involve the proximity of whales to one another. Perhaps the whales in this location were positioned closer to one another allowing for more tactile or visual communication to take place thereby lessening the dependence on the acoustic mode of communication as seen in other species of marine mammals (Paulos, Dudzinski, & Kuczaj, in press).

Consistency was observed not only in the occurrence of codas before and after creaks, but also in the coda group (as defined by the number of clicks the coda contains) that these codas belong to. The two buoy locations located farthest from shore and moored in 800 and 1,000 m of water (E2 and E1 respectively) contained more 6 click-codas both before and after a creak occurrence, whereas, the E3 location (closest to shore and moored in 600 m of water) contained more 4 click codas both before and after a
creak. This pattern would be expected as it mirrors the majority coda group at each location (E1 and E2 had more 6-click codas than any other group and E3 had more 4-click codas).

A wider variety of creak types were identified when codas were present versus when codas were absent. At least one of each type of previously defined creaks was identified in the presence of codas. Conversely, only seven of the 16 atypical creak types were identified in the absence of codas. A majority of these (166 of 179) were of the 2-plus or 3-plus types. The lack of variety observed in the creak types occurring when codas were absent may simply be a result of the small quantity of these “coda absent” creaks. Only 810 creaks occurred without codas present, and only 179 of those fit the description of an “atypical” creak, with leading or trailing coda-type clicks.

When all creak types were pooled and the number of creaks with codas present versus the number of creaks with codas absent were examined by EARS buoy location, there was an overall significant difference between three recording locations. Therefore, despite consistency within each location’s recordings, there appears to be more differences than similarities in the co-occurrence of creaks and codas between buoys.

Limitations

Several limitations in the present study must be taken into account before any potential implications can be considered. 1) No observational data were available to correlate behavior with vocal activity because of the method of acoustic recording employed. In this regard, towed arrays are a better choice of data acquisition because of the potential for simultaneous visual observation of the vocalizing whales. Similarly,
DTAG recordings (using digital tags that attach to the whales dorsal surface with a suction cup, Johnson & Tyack, 2003) increase the information available to researchers by recording the sounds heard and made by the tagged whale along with the whale's depth and orientation. Further benefit of the DTAG method includes the potential for genetic analysis using the skin that sloughs off when the tag detaches from the whale’s body. 2) Because of the positioning of the three hydrophones in a straight line, triangulation methods to localize phonating whales could not be used. Knowing the positions of the whales producing the vocalizations, particularly their depth in the water column, would be information vital in determining if the shorter duration creaks this population produced were truly all being made at the surface or if some were simply unusually short foraging creaks produced at depth. 3) The sampling rate of 11.7 kHz in the present study was sufficient to detect sperm whale clicks, but too low to provide enough detail to examine the structure of those clicks. A higher sampling rate would also have provided the detail necessary to tease apart the closely-spaced clicks of creaks and allow for measurement of their interclick intervals.
CHAPTER VI
CONCLUSION

The similarity in coda patterns between this study and another study from the same location, combined with historical sightings and a lack of temporal variability in coda production identified in other studies, supports the theory that a resident population of sperm whales might inhabit the Northern Gulf of Mexico. Coda types were more similar between the present study and the Apple (2002) study also conducted in the Northern Gulf of Mexico, than between the present study and those conducted in other regions of the world including parts of the Pacific, the Mediterranean and the Caribbean Seas.

The Apple (2002) study collected recordings from the entire northern section of the Gulf of Mexico from the Texas-Mexico border to the Florida panhandle as well as farther east and south of the present study’s recording locations. The similarity in coda repertoires between Apple’s data and the present study could be a result of some vocalizations occurring closer in proximity to each other. As a result of the nature of the way in which the codas were recorded, some towed array recordings from the Apple study would have been obtained closer to the EARS buoy locations than others. According to Rendell and Whitehead (2005), codas recorded within 200 km of each other tend to be more similar than codas separated by distances greater than 200 km. The similarities and differences in coda production lend further support to the premise that group-specific dialects and geographical variation are present in sperm whale coda repertoires.
A location analysis to determine if there was a difference in coda production from one EARS buoy recording location to the next revealed that the recording location in the deepest water recorded significantly fewer codas than the two recording locations closer to shore. This difference could be an indication that the deeper water at the EARS 1 buoy location was in an area of increased foraging, thus whales were socializing less. Or more simply, there could have been fewer whales around the EARS 1 location leading to fewer vocalizations. An analysis of creak production and location supports this more simplistic explanation with fewer creaks also recorded in the area of EARS 1 than at the EARS 2 or EARS 3 recording locations.

A time-of-day analysis revealed that codas were produced with varying frequency throughout the day, but the period with the fewest codas spanned the hours 0600 – 1159. This reduction in coda production could be attributed to a cyclical pattern that includes foraging then reduced vocalizations while at the surface. Furthermore, the peak production of codas occurred during the hours of 1800 – 0559. This differs from the findings of Apple (2002) in his study of whales in the same region. He reported many fewer codas during the last period of the 24-hour day. This difference could be attributed to the methodology employed for data collection (towed array vs. stationary hydrophones), with a mobile mechanism perhaps moving through an area where whales are stationary and being out of range before all codas produced could be recorded. Furthermore, the EARS buoys were moored in an area with frequent boat disturbance that could have impacted the timing of socializing and foraging behavior.

An analysis of the co-occurrence of codas and creaks was executed with a preliminary examination of creak characteristics. Perhaps the most significant finding in
this study relates to the duration of the creaks recorded at all three EARS buoy locations. Overall, 98.9% of the creaks in this study had durations less than 4.0 s, an indication that these were socializing creaks and not foraging creaks. Typically, creaks associated with foraging have longer durations, generally 5 – 45 s. The abundance of short duration creaks identified here may be an indication that the sperm whales recorded in this study are participating in a large amount of socialization activity in this location. Conversely, the short duration creaks could indicate an abundance of prey items making the capture easier, thus resulting in a shorter terminal buzz.

Further support of the theory that much socialization activity was occurring during the present study came from the analysis of the co-occurrence of codas and creaks. Overall, 81.5% of all creaks produced, occurred in the presence of codas. Creaks are often heard in the presence of codas when whales are at the surface socializing, while they are rarely heard at depth from foraging whales.

While the findings revealed herein may expand the knowledge base regarding coda repertoires and acoustic behavior of sperm whales in the Northern Gulf of Mexico, further research is called for to supplement the existing data. The limitations inherent in this study prevent us from knowing the location of the whales as they vocalize, an important piece of the puzzle in determining the potential function(s) of the vocalizations. Interdisciplinary studies combining acoustic recordings with behavioral observation and genetic analyses are needed to provide further support to the current findings and further expand on the context and function of the anomalies and similarities uncovered here. Furthermore, comparative studies utilizing information from disparate parts of the world might ultimately aid in the protection and management of this protected species.
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