SOUND PRODUCTION OF THE HUMPBACK WHALE (MEGAPTERA NOVAEANGLIAE, BOROWSKI) IN NEWFOUNDLAND WATERS

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Sound production of the humpback whale

(*Megaptera novaeangliae*, Borowski)

in Newfoundland waters.

by

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Abstract

Sounds produced by humpback whales, Megaptera novaeangliae, were recorded in Newfoundland inshore waters. Only the acoustic features of the sounds were available for classification. Because of the variability present in the data, measurements such as minimum and maximum frequency, duration, etc, were inadequate for establishing a catalog. A new coding method was experimented with, where each sound was digitized into a matrix (16 x 21) of binary data. This was done using a digitizing tablet and a spectrogram of the sound. Additional binary variables were subsequently added to the matrices to code for relative intensity within a sound and frequency and amplitude modulation. A total of 1255 sounds were digitized and clustered using average linkage cluster analysis and the Jaccard similarity coefficient for binary data.

The classification obtained by cluster analysis was compared with the author's aural and visual impressions of the sounds. A final classification of 50 classes was obtained. These classes were arranged in 13 groups. Three modes of sound production were recognized: respiratory noises, percussion noises, and vocalizations. Most classes (46) recognized in this study appeared to be vocalizations. Some sounds were found to be tonal, but many had noisy and pulsive components. Few classes were stereotyped: variability was often important within classes, and intermediate cases were often found between classes, suggesting that part of the humpback's repertoire is a continuum of graded signals.

Frequency of occurrence of each class varied from 1 to 194. A few classes were very common: the five largest classes accounted for 53.1% of the data. Twelve classes had only one case. This catalog is essen-

tially complete for the location and seasons sampled, as suggested by an estimate of sample coverage and the rate of discovery of new classes with increasing sample size.

Direction finding devices and playback experiments should be used to assess if humpback whales can discriminate these sound classes, and investigate their function.

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INTRODUCTION

This study deals with the sound production of humpback whales, *Megaptera novaeangliae* (Borowski), in Newfoundland waters. In this introduction, a short review of their natural history is given, since data gathered in the last few years on their biology and social system is relevant to their communication system. Next, the importance of acoustic communication for cetaceans will be stressed. A review of cetacean vocalizations recorded to date will follow, with emphasis on humpback vocalizations. Finally, the problems of classifying sounds will be discussed.

THE HUMPBACK WHALE

Description. The humpback is a baleen whale of the family Balaenopteridae, which also includes the blue whale (*Balaenoptera musculus*), fin whale (*B. physalus*), sei whale (*B. borealis*), Bryde's whale (*B. edini*), and the minke whale (*B. acutorostrata*). By comparison with the other members of the rorqual family, it is a mid-sized whale. Males can reach 17.5 m (mean = 14.6 m), females 19 m (mean = 15.2 m) and calves are about 4.5 m at birth (Watson 1981). It is less slender than the other rorquals (Katona *et al.* 1977), which is reflected in its slow swimming speed: 12 km/hr when swimming fast, but normally 6-8 km/hr (Watkins *et al.* 1981). The number of ventral grooves is also less than in other Balaenopteridae: 14-24 (mean 22) (Watson 1981). The head is broad and rounded, without a ridge but covered with knobs from the extremity of the snout to the blowhole. The dorsal fin is small and quite variable in shape, mounted on a fleshy step or hump slightly more than 2/3 of the way back (Leatherwood *et al.* 1976; Watson 1981). A major characteristic is the pair of very long pectoral fins or flippers. They can reach 1/3 of the length of the animal, almost 5 m in the adult, and have a scalloped leading edge (Leatherwood et al. 1976; Watson 1981). The baleen plates are black with black or olive bristles. The tail is frequently raised above water when the whale initiates a deep dive. Its trailing edge is serrated (Leatherwood et al. 1976).

Pike (1953) gives True's (1904) observations of European humpback coloration as representative of all humpbacks: the color is normally black on the head, back and sides and around the caudal peduncle; the color of throat and chest and the median line below, at least as far back as the anus, is varied to a greater or less extent with white spots, streaks and larger areas; the flippers have the lower surface mostly white, with the upper surface varied white and black; the flukes are largely black above, more or less white below. This last characteristic is used to identify individual humpbacks (Schevill & Backus 1960; Katona et al. 1979). This is possible because the flukes' coloration is distinctive for each animal and does not evolve much over the years. There are some developmental changes in fluke pigmentation (S. Mayo, pers. comm.) and sometimes addition of marks resulting from contact with sharp objects (rocks, fishing gear, killer whale teeth), which may confound long term identification. But in one case, a whale was still recognizable 14 years after the first time is was photographed (Katona et al. 1982). Pigmentation and scars on the back, dorsal fin and flippers of the animals are also used for individual identification (Schevill & Backus 1960; Katona et al. 1979; Glockner-Ferrari 1982; Glockner & Venus 1983).

Humpback whales carry many barnacles and whale lice on their chin and throat, trailing edge of flipper, around the genitalia and at the tips of the tail (Leatherwood 1976).

Except for a female with a suckling calf or when the pigmentation pattern can be identified from a previously sexed animal, it is almost impossible to distinguish between males and females at sea. Observation of the genital area is the only known method. It is possible only when the animal rolls over at the surface and at close range, or by sending a diver under the whale, as in Glockner-Ferrari (1982) and Glockner (1983). Matthews (1937) claimed that at least for southern hemisphere humpbacks, females were darker. Pike (1953) found that more males (73% vs 33%) had very dark flukes in eastern North Pacific. Herman & Antinoja (1977) found that males and females were represented similarly in their four classes of flipper coloration. Coloration appears to be too variable to be used in sexing humpback whales.

Recently two methods of sexing these animals were proposed. Jurasz _et al._ (1980) suggested that the shape of the back between the dorsal fin and the tail was different for males and females. Whitehead (1980), because of the marks commonly left on the dorsal fin of humpbacks engaged in agonistic interactions and believed to be males, suggested that a humpback with a very smooth dorsal fin was likely to be a female. Both hypotheses await more data. However Winn _et al._ (1973) suggested a cytological method that does not give immediate results but seems to be reasonably accurate: if a small skin sample can be obtained, cytological examination can determine the sex of the animal, by counting the number of sex chromatin bodies present in the nucleus. Similarly, sexing can be done by cutting skin samples with a modified arrow, and karyotyping (J. Lien, pers. comm.).

Migrations and reproductive cycle. Like most baleen whales, humpbacks undertake long seasonal migrations. Since humpback often migrate along shorelines, their migrations were known early (Scammon 1874; Kellog 1929). Today it is well known that these whales are found between 50° and 70° of latitude in summer, and between 0° and 30° in winter (Mackintosh 1965). Migrations are intimately related to the physiological cycle. Humpbacks are feeding and accumulating fat reserves during the summer spent in productive polar waters. They rarely feed when on the tropical grounds, as not much food is available (Mackintosh 1965; Dawbin 1966; Herman 1979; Whitehead & Moore 1982). Their presence in high concentration in tropical waters is related to reproduction. Calving occurs at this time, and new-born calves, having a thin layer of blubber and a greater surface to volume ratio do not suffer a thermal shock in warm waters (Whitehead & Moore 1982) (but Kanwisher & Sundnes 1966, argued that calves of most large species of whales are born with enough blubber for thermoregulation). Breeding is also thought to occur there, even if no definite mating has been observed (Tyack 1982). Reviewing several papers, Tyack gives the following evidence for winter to be the mating season: mature male humpback whales show an increased testis weight and increased spermatogenesis during the winter, females ovulate in the same season and the vast majority of them bear their calves in the winter (since the gestation period is about one year, it suggests that mating must occur during the same season).

Kellog (1929) noticed that females with calves arrive later in season on the feeding grounds than bulls and nonbreeding cows. Later, Dawbin (1966) found a segregation by classes in southern hemisphere migrating humpback. In spring, pregnant and resting females, immature whales, mature males and finally lactating females depart for the feeding areas. In fall, the order is different: females with yearlings (end of lactation), immature males, immature females, mature males and then pregnant females leave for the breeding area. Arrival of sex/age classes in Newfoundland does not follow strictly this order: larger whales arrive in the middle of the season (Whitehead <u>et al</u>. 1982). Day-length might be the initiating factor of humpback whale migrations (Dawbin 1966).

<u>Populations.</u> There are several populations of humpback whales, both in northern and southern hemispheres. Mackintosh (1965) distinguished six populations in the southern hemisphere, and two in the northern hemisphere: North Pacific and North Atlantic. He suggested that there was some segregation between the humpbacks of eastern and western waters of these two oceans. Fluke photographs can help follow humpbacks in their migrations, when whales are photographed on more than one occasion and in different locations. The northwest Atlantic population, which is of interest for this study, has been extensively photographed since the early 1970's. Whales have been photographed on the breeding grounds, the West Indies, and on several feeding grounds: Gulf of Maine, Nova Scotia, Gulf of St.Lawrence, Newfoundland and Labrador, Greenland, and Iceland. Fluke data indicate that these animals share their breeding grounds but segregate in several substocks on the feeding

grounds: no whale was photographed in more than one of these four feeding regions: Nova Scotia-Gulf of Maine, Newfoundland-Labrador, Greenland, and Iceland (Katona et al. 1982; S. Katona, pers. comm.). The sample size is too small in the Gulf of St.Lawrence, however no whale seen there was seen on any other feeding region either (Katona et al. 1980). Recent data (R. Sears, pers. comm.) will further clarify the status of Gulf of St.Lawrence humpbacks. Katona et al. (1980) suggested that, since whales of all feeding grounds are in close spatial proximity on the breeding grounds, whales return to the feeding grounds they first visited with their mother.

Mitchell & Reeyes (1982) estimated the 1865 virgin (prior to whaling) population for the northwest Atlantic population at 4200 and probably more. The latest technique to estimate today's population size is the use of capture-recapture method with fluke photograph data. The population would be 3000-5000 individuals (Katona et al. 1982). Mitchell & Reeves (1982) prefer a more conservative estimate of 1500-2000 whales, but the fluke catalog already contains slightly more than 2400 individual photographs (S. Katona, pers. comm.) and present photographic recapture rates make it unlikely that all whales have been photographed.

Feeding. Depending on what population or substock they belong to, humpback whales feed on krill and various schooling fish (Jonsgard 1966; Nemoto 1970; Leatherwood et al. 1976; Watson 1981). Nemoto (1970) described two basic feeding modes in baleen whales: swallowing and skimming.

> "Swallowing type whales (blue, fin, Bryde's and humpback whales) swallow the food found in the patch or swarm, along with water, then discharge the sea water through the baleen plates while the food remains in the mouth cavity" (Nemoto

1970, p. 246).

Within this type, humpbacks use different strategies according to their population and the species of prey: lunge feeding, bubblenets, flickfeeding, diving into deep schools, etc. (Jurasz & Jurasz 1979; Watkins & Schevill 1979; Hain et al. 1982; Bredin 1984). In Newfoundland, they feed on krill in early spring (Bredin 1984), but principally on capelin (Mallotus villosus) (Mitchell 1973) through-out the summer. Squid (Ilex illecebrosus) has also been found in their stomachs (J. Lien, pers. comm.). They use lunge feeding (short dive followed by a rush toward the prey at the surface, the open mouth often breaking the surface of the water) on krill, spawning capelin and squid, and dive to get deep schools of prey in late summer (see Bredin 1984, for details).

Social system. Since feeding and reproductive activities are segregated seasonally, it is not surprising to find that the humpback whale's social system is quite different in winter and summer. Nemoto (1964, in Herman & Antinoja 1977) reported that 50% of the 92 pods he observed in the North Pacific feeding grounds were singles. Pairs accounted for 43% and 7% were in groups of at least three whales. Whitehead et al. (1982) also noted that grouping was labile in Newfoundland waters, and that whales that were seen together on one occasion were not more likely to regroup later than any other whales.

On the other hand, whales on their breeding grounds were seen more often in large groups of up to 15 animals (Tyack & Whitehead 1983). In Hawaii, 41.5 % were singles, 26.1% in pairs, and 32% in groups of three or more (Herman & Antinoja 1977). Whale density can be very high (1 per square km on Silver Bank, in the West Indies, Tyack & Whitehead 1983). Herman & Antinoja (1977) noted that single whales or mother and calf were swimming more slowly in Hawaii than multi-adults pods. Tyack (1982) reported that pods with two adults were less active than larger groups. Tyack and Whitehead (1983) found that these large groups were in fact engaged in much physical and acoustic activity.

Structure of these large groups and their behavior was the same for humpbacks observed in Hawaii and Silver Bank (Tyack and Whitehead 1983). An adult, called the "nuclear animal", is the center of attraction and indifferent to the other whales. Nuclear animals were frequently the mothers of calves. The other animals were actively competing to get, and then to stay, in physical proximity to the nuclear animal. They were called "escorts", the animal closest to the female being the "principal escort" and the others "secondary escorts". The authors believed that escorts are males as no escort was ever seen with a calf and, in the simpler cases where a female had a single escort, all escorts (21) that were sexed were males (Glockner-Ferrari & Ferrari 1982, cited in Tyack & Whitehead 1983; Glockner 1983). The principal escort would put its body in the way of any secondary escort (the challenger) that would try to get between it and the female. Contact between males was sometimes fairly violent. They also noted that often (9% of attempts) one challenger whale would be successful in dislodging the principal escort and becoming the new principal escort. Tyack and Whitehead (1983) wrote that even if no mating was observed, such fierce competition indicates that the principal escort likely has better chances of mating with the nuclear animal.

COMMUNICATION CHANNELS AVAILABLE TO CETACEANS

Need for a communication system. Humpbacks are often seen in pairs and more rarely in larger groups on their feeding grounds, and are very gregarious on their breeding grounds. Similarly, other mysticetes (baleen whales) and many odontocetes (tooth whales) are social, at least during their breeding season (Mackintosh 1965; Payne & Webb 1971; and Watson 1981). Complex interactions have been described for many species (e.g., Wursig & Wursig 1980, for dusky dolphins *Lagenorhynchus obscurus*; Clark 1982 and 1983, for right whales *Eubalaena australis*; Tyack & Whitehead 1983, for humpbacks; and others). These animals must exchange information in one way or another about swimming speed and direction, sex, reproductive status, etc. Schaller (1972, p. 83) said: "The successful functioning of a society is entirely dependent on its communicatory system..." Many definitions of communication can be found. Hailman (1977, p. 21) gives the following:

> "Communication may occur when a sender initiates in some channel a physical disturbance (the signal) that is detected by a receiver."

Klopfer & Hatch (1968, p. 32) explained how to recognize communication empirically:

> "The ultimate criterion for recognition of the occurrence of communication is that of a resultant change, sometimes delayed, sometimes scarcely perceptible, in the probability of subsequent behavior of the other communicant."

For Hailman (1977), communication is a very broad concept, which can be subdivided. For example, animal communication is a subset of communication where both sender and receiver are animals. Similarly, social communication is a special case of animal communication consisting of reciprocal exchange of signals between conspecifics with use of specialized structures or behaviors. In this thesis, communication is used in the restricted meaning of social communication, unless otherwise stated.

A communication channel is the physical medium that is used to send a signal (Hailman 1977). The list of possible media would include the tactile channel (e.g., physical contact), the electrical channel (emission of electric charges), the chemical channel (involving the use of chemical compounds), the optical channel (emission of light and/or modification of ambient light) and the acoustic channel (production of sounds or modification of ambient sound). As it can be seen by looking at any general text on the subject (e.g., Sebeok 1977; Smith 1977) most organisms make use of several channels in their communication system. Each channel offers its own advantages and limitations. Obviously, a given organism is limited by its capacity to produce some disturbance in a medium (the signal), as well as by the capacity of a conspecific to perceive this signal, before any transfer of information can be carried out. The environment also imposes limitations on the use of the various channels. Two important constraints are the transmission characteristics of the channel in a given environment, as well as the naturally occurring disturbances in the channel (noise) that might mask the signal. In other words, anatomy and physiology of a species, physical properties of a channel in the habitat and presence of noise are the limiting factors for communicatory use of the channel by this species.

In the next pages, performance characteristics of each channel in the oceanic environment will be discussed, as well as the abilities of whales to produce and receive signals in each one. The electric channel is not included, since marine mammals do not use it (Herman & Tavolga 1980). There is often little data available on the sensory physiology of baleen whales, and one has to be careful in extrapolating results from odontocetes.

Tactile signals. The properties of this channel are the same in and out of water. Its limitation is that, by its nature, it becomes useless when the animals are at a distance. Its directionality is advantageous: it allows the sender to select the receiver when many conspecifics are present. The fact that it requires physical contact between the communicants might be advantageous in facilitating further interactions. Tactile signals can be energitally more costly than other signals. Behavioral and anatomical evidence reveal a good tactile sensitivity for cetaceans (Slijper 1979; Herman & Tavolga 1980). They use tactile signals in activities such as courtship and mating, nursing and agonistic situations (McBride & Hebb 1948; Payne 1976; Herman & Tavolga 1980; Clark 1983; Tavolga 1983; Tyack and Whitehead 1983).

Chemical signals. The rate of propagation of chemical compounds depends on the fluidity of the medium in which they are released. Chemical dispersion is generally slower in water than in air (a few meters per second, Schevill et al. 1962), but depends on currents and other water movements. This precludes its use for fast changing signals, but can be advantageous when long lasting messages are needed: the reduction of the need for repeating messages can be of considerable economy (Wilson 1975).

Odontocetes have no olfactory receptors and mysticetes have very reduced olfactory nerves, bulbs and peduncles in comparison with terrestrial mammals (Herman & Tavolga 1980). Even if it is functional, baleen whales would be limited to aerial olfaction, since their nares are always closed when underwater, except when air is expelled. Caldwell &

Caldwell (1977) and Herman & Tavolga (1980) reported some studies indicating that cetaceans may still have taste discrimination. Norris & Dohl (1980) suggested that feces and urine might be used by ceteceans to transmit information about sexual readiness. Chemical signaling is at best very limited in cetaceans, with poor reception added to slow propagation.

Optical signals. Transmission of light is greatly reduced underwater, especially in waters rich in nutrients and marine organisms, and vision is often possible only at ranges up to a few meters (Schevill et al. 1962). This channel cannot be used at night, except maybe at very short distances (Kinne 1975). Within these limitations, the optical channel has great communicatory potential: it can carry very complex signals instantaneously and support a very high rate of signaling (Hailman 1977; Herman & Tavolga 1980; Schevill et al. 1962).

Studies reviewed in Herman & Tavolga (1980) and Madsen & Herman (1980) revealed that oceanic odontocetes have a wide field of vision, good brightness and movement detection, and are sensitive to those wavelengths that dominate in the euphotic zone. Visual acuity is good at 1 m, but deteriorates rapidly with distance. Color vision is probably weak or absent and discrimination of abstract-forms is poor. At least for the bottlenosed dolphin (Tursiops truncatus), long distance aerial vision is fairly good (Herman et al. 1975). Not much is known of mysticete vision. The relative number of fibres in the optic nerve suggests better vision in mysticetes than odontocetes (Kinne 1975).

Cetaceans can produce optical signals passively (presence vs. absence, body coloration, orientation) or actively (by adopting special postures and behaviors) (Hailman 1977; Herman & Tavolga 1980; Madsen &

Herman 1980). Social communication is only one function of body coloration, as it can evolve in response to several selection pressures: thermoregulation, feeding success, predation, social environment, etc. (Hailman 1977). For example, some studies show a correlation between coloration and feeding habits: cetaceans feeding on slow moving prey items or in near darkness are uniformly colored, but those which feed on faster prey under conditions of good visibility tend to be cryptically colored (Madsen & Herman 1980). Brodie (1977) also hypothesized some deceptive functions of the white coloration of North Atlantic humpback whale flippers and the white patch present on North Atlantic minke's flippers: these whales feed on fast moving schooling fish and might use their flippers to herd the fish toward their mouth. He added that populations of these two species that feed on slower prey have darker flippers. This function of coloration does not preclude its use for social communication (predator-prey interactions and intraspecific or social communication are two subsets of animal communication in Hailman's classification (1977)), as often contrasting patches are found on species that tend to travel in large groups (Madsen & Herman 1980). In summary, the optical channel is restricted to short distance communication in cetaceans, and more likely to be well developed in very gregarious species. In these cases, its possible uses are coordination of group movements, identification of species, sex, age and identity, courtship, nursing, communication of physiological and behavioral states (Madsen & Herman 1980; Tavolga 1983).

<u>Acoustic signals.</u> Sound transmission is often efficient even over long ranges underwater (Schevill <u>et al</u>. 1962; Herman & Tavolga 1980). The speed of sound varies directly with temperature and pressure (Payne

& Webb 1971), but is about 4.5 times faster underwater than in air (Kinne 1975). Four factors affect the distance over which a sound is audible: the transmission characteristics of sound in the environment, the level of background noise, the sound intensity at the source, and the sensitivity of the receiver (Morton 1975; Waser & Waser 1977).

The main factors affecting sound transmission are geometrical spreading, attenuation and sound redirection. Geometrical spreading is the reduction in sound intensity caused by the expansion of the wave front (Lyon 1973; Morton 1975). The effects of geometrical spreading on sound propagation depend principally on water depth and stratification of the water column (Payne & Webb 1971). Attenuation is due to dissipation of energy as heat owing to the viscosity of the medium and to molecular absorption (Piercy et al. 1977; Wiley & Richards 1982). Attenuation is proportional to distance and frequency: low frequencies will transmit much further than high frequencies (Payne & Webb 1971). Sound waves can also be redirected by refraction, reflection, diffraction and scattering, thus affecting sound intensity at the receiver's location (Ingard 1953; Lyon 1973; Wiley & Richards 1978). Like attenuation, sound redirection is more important for higher frequencies.

Background noise is more or less important, according to the frequency and the local conditions. In general, noise decreases with increasing frequency (Wenz 1964). In the very low frequencies (1-100 Hz), noise is always important. Its causes are oceanic turbulence and pressure fluctuations, microseisms and occasionally, earthquakes, explosions, etc. Oceanic traffic is the most important source of noise in the 10-1000 Hz range, while surface agitation, which is weather dependent, affects mostly the 100-1000 Hz range, but creates noise in frequencies as high as 50 kHz. Biological sources can also make noise in frequencies of 10-50000 Hz (Wenz 1962 and 1964; Caruthers 1977).

The acoustic channel can transmit very complex signals at very high rate and can be used day and night (Busnel 1963). It often offers the best potential for efficient and effective cetacean communication.

In the last few decades, odontocetes have been successfully kept in captivity. Using conditioning and neurological techniques, several studies of odontocete hearing (reviewed in Herman & Tavolga 1980; Popper 1980; Ljungblad et al. 1982) revealed excellent hearing capabilities, fine frequency discrimination and highly precise sound localization capabilities. Audiograms of several species show sensitivity over as many as 10 octaves.

Studies of mysticete hearing are more difficult. Whalers knew that baleen whales had good hearing (Herman & Tavolga 1980), and more recently, anatomical studies revealed that they have an acute sensitivity for low frequencies, but probably lack the very high-frequency hearing capabilities of odontocetes (Herman & Tavolga 1980). Since odontocetes were found to hear best in the frequencies they use for sound production, the same can be assumed for mysticetes (Caldwell & Caldwell 1977). Most mysticete sounds published to date have their fundamental below 2000 Hz, which corroborates the anatomical data. In the future, playback experiments could be used to more precisely define their hearing capabilities.

Finally, the capacity of cetaceans to produce sounds is well known. Scientific reports of cetacean sounds abound (for reviews, see Evans 1967; Poulter 1968; Caldwell & Caldwell 1977; Herman & Tavolga 1980).

It is clear that cetaceans took advantage of the good transmission characteristics of the acoustic channel. They can produce signals that are transmitted over long distances. Dusky dolphins sounds can be heard by human beings at more than 0.5 km (Wursig & Wursig 1980), while sperm whale (Physeter catodon) clicks can be transmitted over more than 10 km (Watkins 1980). Humpback whale song units have been recorded at 2.5-20 km (Payne & Guinee 1983). A theoretical range of 83 (with spherical spreading) and 972 km (cylindrical spreading and special depth conditions) have been calculated for the fin whale's 20 Hz signals (Payne & Webb 1971)). Sounds can carry information about location, species, sex, identity, activity, physiological and behavioral state or serve to coordinate behavior (Madsen & Herman 1980; Ford & Ford 1981; Steiner 1981; Tyack 1981 and 1983; Clark 1982; McLeod 1982; Ford & Fisher 1983). Odontocetes also use sounds to detect prey or obstacles (i.e., echolocation, see Norris et al. 1961) and may use them to stun prey (Norris & Mohl 1983).

CETACEAN SOUNDS

Historical records show that Aristotle (in the fourth century B.C.) and, more recently, many whalers (Eighteen and beginning of Nineteen centuries) knew that cetaceans produce sounds (Schevill et al. 1962; Schevill 1964). However scientific evidence came only with increasing use of hydrophones during and after World War II (Schevill et al. 1962; Watkins 1977). Since this time, cetacean sounds have been recorded regularly.

In many cases, it was difficult to ascertain what species of whales were responsible. Often, the equipment could not cover the entire frequency range of the sounds. Loss of the high frequencies was common with the equipment used in the fifties and early sixties (e.g., Schevill et al. 1962). More recently, most researchers have used equipment recording at least up to 10 kHz. But unless special precautions are taken, low frequencies are still frequently masked by ocean and equipment noises (Cummings et al. 1968).

Thompson et al. (1979) reviewed the literature on mysticete sounds. All species but the pygmy right whale (Caperea marginata) are known to produce sounds (if sound origin was correctly assessed in all the studies). But the information is very fragmentary for several species. Sounds of several baleen whales have similar acoustic properties. Winn & Perkins (1976) and Thompson et al. (1979) divided them in four broad classes and listed the species known to make sounds in each class. The first group includes low-frequency moans 0.4-36 sec long, with fundamental frequencies of 12-500 Hz. All baleen whales except the sei and minke whales are said to produce such sounds. Gruntlike thumps and knocks of shorter duration form the second class. They range from 40-200 Hz and 50-500 msec and were recorded from all species but the blue, sei and Bryde's whales. "The third group contains chirps, cries, and whistles at frequencies above 1000 Hz." (Thompson et al. 1979, p. 425). Humpback and gray whales are known to produce these sounds. Clicks and pulses of very short duration are the fourth class. They last 0.5-5 msec and their bandwidth varies from species to species. Such sounds were recorded in presence of minke, gray, humpback, sei, Bryde's, fin, and blue whales.

All these sounds are well into human hearing range. The blue whale (Beamish & Mitchell 1971) and maybe the fin whale (Thompson et al. 1979) are thought to utter ultrasonic (above human earing capabilities) emissions.

Because several species of odontocete echolocate well, every time that a baleen whale was found to produce sounds of the fourth class (clicks and pulses), the possibility that they too might echolocate was raised. Very rarely were the acoustic properties of the clicks investigated to see if they could, at least in theory, be used to detect the favorite prey of the whale, as in Beamish & Mitchell (1971 and 1973). However, echolocation has never been demonstrated in mysticetes. Beamish (1978) reported the only controlled experiment on the matter: a blindfolded humpback ran silently into obstacles instead of emitting the clicks that the species is known to produce.

HUMPBACK WHALE VOCALIZATIONS

Early reports. Rawits (1900, cited in Slijper 1979 and Watkins 1967a) describes a noise resembling a siren that was made by a school of forty humpbacks. The frequency of these howling blows first increased, but decreased at the end. Similar "wheezing" blows have been recorded by Watkins (1967a) who confirmed Rawits suggestion that they are caused by constricting the nostrils. Contrary to normal blows, wheezing blows are clearly audible underwater (Watkins 1967a).

Whalers knew that humpbacks produce sounds underwater (e.g., Aldrich 1889; Nordhoff 1940), but the first recordings are probably those of Schreiber (1952), from Hawaii. Sounds of "rather musical quality" were recorded in early spring, during the seasonal presence of whales (Schreiber 1952, p.116). According to Herman (1979), the only species of whales present in the area at that time of year are humpbacks. Schevill et al. (1962) reported that low frequency sounds (300-400 Hz) were recorded from humpbacks. In a later paper (1964, p. 310), Schevill reported a seasonal effect:

> "The sonorous moans and screams associated with the migrations of *Megaptera* past Bermuda and Hawaii may be an audible manifestation of more fundamental vernal urges, for in New England waters and at other seasons we do not hear anything nearly so spectacular from this species".

Humpback song. Watlington in Bermuda (in Payne & McVay 1971) and Kibblewhite et al. (1967) in New Zealand also recorded numerous sounds from humpbacks migrating toward their breeding grounds. In the later study, the sounds were called the "Barnyard Chorus" and consisted of "a chorus of squeals, creaks, cries, barks, groans, and whoops" (Kibblewhite et al. 1967, p. 644). Payne & McVay (1971) studied Watlington's tapes and found that the sounds humpbacks utter in Bermuda corresponded to a definition of song given by Broughton (1963, p. 883):

> "a series of notes, generally of more than one type, uttered in succession and so related as to form a recognizable sequence or pattern in time".

Since this early work, humpback songs have been recorded on the breeding grounds of both the North Pacific (Hawaii) and the Northwest Atlantic (the Caribbeans) populations (Winn et al. 1970; Payne 1978; Winn & Winn 1978; Whitehead & Moore 1982; Payne et al. 1983).

The humpback song is the most complex vocalization reported from a whale, and from any animal according to Wilson (1975). Tyack (1982) has commented on this presumed complexity. A song is composed of different units, which are the shortest sounds that are continuous to the human ear in real time (Payne & McVay 1971; Payne et al. 1983). Units are not uttered at random, but organized into short sequences called phrases. Phrases can be repeated a variable number of times, to form a theme. Several themes form the song. An animal will usually start singing again almost without break after it finished a song, thus producing a song session. From one utterance of the song to the next, some themes may be deleted, but the order of the remaining themes is very predictable.

Winn et al. (1970) studied singing humpback in the West Indies and found that one sequence of the song, called the surface ratchet, correlates with the surfacing of a whale, presumably the singer. Winn & Winn (1978) also reported that songs are always uttered by lone individuals. This fact has been confirmed by Tyack (1982), who recorded 96% of his songs from single whales, and Whitehead (1981), who found 94% of his singers to be alone. Tyack's work in Hawaii (1982) presents the first evidence that humpback song is a courtship display. As in Winn & Winn (1978), the few singers that were sexed were males (with one possible exception). Also, nearby groups would swim away from a singer, or toward it, depending on their composition (Tyack 1981, 1982 and 1983).

Payne (1978), Winn et al. (1981) and Payne & Guinee (1983) found geographic variation in the song. Animals from the Pacific and the Atlantic have different songs, even if they share the same song format (Payne et al. 1983). For both breeding stocks, it was noted that the song changes from year to year. The reasons for this are not clear. It is not that whales forget some details of their song during their feeding season, since Payne et al. (1983) found the song at the beginning of a breeding season practically unchanged since the preceding spring. In fact, the changes take place progressively during a breeding season. Since it is suspected that whales do not remain at the same place but continuously move through their breeding area (Herman *et al.* 1977), changes in the song might be caused by this turnover of singers. But a study by Guinee *et al.* (1983) ruled out this hypothesis: known individuals recorded several times during a singing season had changed their song, along with the rest of the whales. Having found that themes grow in complexity and then begin to deteriorate, Payne *et al.* (1983) proposed that this continual modification of the song results from female humpbacks selecting males with a complex song. It is still not clear why all males sing the same song at a given time, if selection is for song complexity. Maybe some whales gain in adopting the song of other whales, like inexperienced indigo buntings (*Passerina cyanea*) increase their reproductive fitness by mimicking the song of successful males (Payne 1983). Some female songbirds are especially stimulated by exposure to more varied song repertoires (Kroodsma 1976).

Social sounds. The song is not the humpback's only vocalization. Other sounds have been recorded during the breeding season and in summer, on the feeding grounds (Schevill 1964; Winn *et al.* 1970; Tyack 1982). Even if they can be produced in sequences, they lack the complex temporal organization of the song. Contextual information is difficult to gather. Some of these sounds were recorded from humpbacks entrapped in fishing gear in Newfoundland (Beamish 1979; Winn *et al.* 1979). Some were recorded from the large active groups described earlier for the breeding grounds (Tyack 1982). In fact, Tyack called these phonations "social sounds" because they were primarily produced by whales in groups, as opposed to the song which is produced by lone whales.

Table 1. Humpback whale's social sounds reported in the literature.

The sounds are grouped into general types. References are listed at the bottom of the table. The descriptions of the sounds were obtained from each publication, and/or by looking at the spectrograms (RR stands for repetition rate, in pulses per second). When a spectrogram was present, its upper limit (UL), its scale (S, either linear or logarithmic) and the analysis filter (AF, na (narrow) or wi (wide), when the value in Hz was not given) are indicated.

SOUND TYPE	REF.	DESCRIPTION	FREQUENCY RANGE (kHz)	PEAK FREQ (kHz)	DURATION (sec)	SPECTROGRAM UL (kHz)	S	AF (Hz)
loud exhalations	[1]	wheezing blow	0-4*	1-1.5*	2*	4	lin	20
	[4]	shriek						
	[4]	trumpetting						
flipper or tail slaps	[4]	broadband pulse						
various moans	[6]	moan with fast RR: 80-15	.05-.6*	.2-.4*	.63-4.55	1	lin	na
	[6]	pulsed moan, slow RR: 25-50	.05-.5*	.2-.4*	.54-5.70	1	lin	na/wi
	[6]	pulsed moan ending in Yup	.05-.6*	.05-.4*	2*	1	lin	na
	[6]	pulsed moan ending in moan	.05-.6*	.2-.4*	5*	1	lin	na
	[5]	ratchet, increasing RR	.1-2*	.1-.8*	4.5*	3	log	300
	[4]	moan						
grunts	[4]	grunt						
yups	[6]	Yup, fast RR	.05-1*	.05-.4*	.11-.29	1	lin	na
	[4]	yelp						
chirps	[6]	pure tone or broadband	1.1-9.5		.04-.15	4	lin	na
cries	[6]	freq modulated	1.3-2.2		.22-.25	4	lin	na
clicks	[2]	pulsive	2-5*	2-5*	.02	15	lin	60
	[2]	double-click				15	lin	60
	[6]	narrow-band		1.5-2.8	.008-.01	12	lin	na
	[6]	wide-band	1-8*		.005-.007	12	lin	na

(continued on next page)

Table 1. (Continued)

SOUND TYPE	REF.	DESCRIPTION	FREQUENCY RANGE (kHz)	PEAK FREQ (kHz)	DURATION (sec)	SPECTROGRAM UL (kHz)	S	AF (Hz)
click trains	[2]	clicks	1-3*	2*	.36*	15	lin	60
	[5]	click train		2.0-2.1				
	[5]	click train		8.2				
	[5]	click train	.5-3*	1*	1.5*	3	log	300
	[4]	pulse train, RR: 1, plus .04-1.2 kHz noise	.25-.8		15-100			
	[4]	pulse train, RR>1, uneven amplitude	>0.5					
	[7]	pulse train	.1-1.5		1.5-20			
others	[1]	(no name)	0-2*	0-.5*	.5*	2	lin	20
	[2]	white-noise blast	1.5-14*	5-8*	.2*	15	lin	60
	[2]	pulsive	1.5-12*	6*	.2*	15	lin	60
	[3]	whooshes	0-4*	.5-4*		5	log	
	[5]	pulsed sounds	0-2*	.2-1.2*	.2-.3*	3	log	300
	[4]	pulses, low and narrow						
	[7]	type 1	0-7*	1 0-1*	1.1*	8	lin	
	[7]	type 15	0-4*	0-1.5*	3*	6	lin	
	[7]	type 25	0-4*	0-3*	2.5*	6	lin	
	[8]	type A	0-.4*	.1-.3*	.8-1*	.4	lin	
	[8]	type B	0-.4*	.2*	.1-.3*	.4	lin	

* approximated from the published spectrogram

[1] Watkins 1967
[2] Winn et al. 1970
[3] Perkins & Whitehead 1977
[4] Thompson et al. 1977
[5] Beamish 1979
[6] Winn et al. 1979
[7] Lawton 1979
[8] Tyack 1982

Lawton (1979) recognized 25 different sound types from humpacks feeding in Alaska, which is more than what has been recorded from any other species of baleen whale. However, no comprehensive list of humpback sounds has been produced.

Most of humpback's social sounds that have been published are listed in Table 1. Sounds recorded on the breeding grounds were excluded, unless it was clear that they were from non-singing whales. Some of the sounds are exhalations, tail or flipper slaps on the surface, or possibly clashing of baleen plates from wave action (e.g., pulse trains reported by Thompson et al. 1977). The others are thought to be vocalizations. Many of the terms used by the different authors to describe vocalizations were not clearly defined, which makes comparisons difficult.

The present study investigates the sound production of northwest Atlantic humpback whales on their Newfoundland feeding grounds

CLASSIFICATION OF A REPERTOIRE

Sources of signal variability. One prerequisite of communication is that the receiver must be able to decode the signal. Some characteristics of a signal must allow its identification by the receiver. Very rarely, however, are all utterances of a signal be identical. Variability is induced at many levels. The first level is called within-individual variation: an animal repeating a signal several times will not produce exactly the same signal each time. As stated by Smith et al. (1982), this variability may be interpreted as random variation or as a systematic variation that conveys some information (see the following discussion on graded signals).

The identity of the signaler is another source of variability. For example, several studies could discriminate statistically the identity of senders by the characteristics of their sounds: Smith et al. (1982), with squirrel monkeys (Saimiri sciureus), Backus & Schevill (1966), sperm whales, Caldwell & Caldwell (1971) and Caldwell et al. (1973), dolphins. It is generally assumed that the animals can also perceive these differences. In some cases, perception of individual differences has been demonstrated: for example, brown hyaena (Hyaena brunnea) recognize other individuals' scent marking (Mills et al. 1980); mother northern elephant seals (Mirounga angustirostris) recognize their pup's vocalizations (Petrinovitch 1974).

Sex and age of individuals can also contribute to signal and repertoire variability. Animals of different sex or age class may use signals that are specific to their sex or class. Signal structure may also be dependent on sex or age (Green & Marler 1979). For example, acoustic signals of several species are size dependent: pitch changes with age, since sound frequency is dependent on the size of the sound production system. Gautier & Gautier (1977), Hafner & Hafner (1979), and Prescott (1979) reported ontogenic changes in signal pitch.

It is advantageous for animals living in stable social units to distinguish between group members and strangers. Information about group membership can be obtained in several ways. Signature information, as described above, can be sufficient to recognize a stranger from a group-mate (i.e., non-familiar from familiar signals, as in coyotes, Canis latrans, scent marking, Bowen & McTaggart Cowan 1980). Sometimes, group membership is an additional source of variability by itself:

group-mates can have signals more similar to each others' signals than to those of outsiders, or groups can use a certain number of unique signals (i.e., signals not shared by other groups, or at least not by all groups). Such group-dependent signals are called dialects and have been frequently reported for birds (Marler 1970; Nottebohm 1970), but also for social odontocetes (e.g., Ford & Ford (1981) and Ford & Fisher (1983) on killer whales, Orcinus orca, and McLeod (1982) on pilot whales, Globicephala melaena).

Finally, distinct populations of a species can present the same kind of variation in their repertoire. In cetaceans, this geographic variation has been reported for the humpback whale, as explained earlier.

Graded signals. Studies on primate vocalizations revealed that species that must rely on a single communicatory channel for most of their needs have discrete signals, i.e., the different signals of their repertoire are well stereotyped, easy to recognize. For example, arboreal primates living in dense forests communicate principally in the acoustic channel, optical communication being possible at very close range only. To avoid information being lost during transmission, most signals are in well categorized classes, little affected by environmental noise (Green & Marler 1979). But when more than one channel is readily available, signals are often graded: no natural boundaries can be found and a complete range of intermediates is present between categories. This is the case in close-range signaling of many primate species. Sounds were graded but richly supplemented by visual and tactile signals, especially for species living in large troops in open environments (Byrne 1982; Green & Marler 1979). With cetacean sounds, one could expect that signals used for long distance communication are discrete, to insure that distortion will not prevent decoding of the information by the receiver. However, animals interacting at close range may be using graded sounds, for the reasons given earlier.

The interpretation of such repertoires is difficult. Should sounds that vary on one or more of their acoustic properties be put in a single category, in a certain number of distinct categories, or in an infinite number of classes? The first approach is simplistic and would not contribute much to understanding a species repertoire. The two others can be appropriate, depending on the species and signals involved. In certain cases, not all the variability is perceived or utilized by the receiver, and continuously variable sounds are perceived as a series of discrete signals, just as human speech is for us. In other cases, graded signals are really a continuum of signals and carry very detailed information on the signaler's behavioral state (Green & Marlers 1979).

It is clear that descriptions of signals are insufficient to identify the different elements of another species' repertoire.

> "It is an obvious but often neglected point that what an animal makes of a signal it receives cannot be determined by analyzing the signal." (Green & Marler 1979, p. 99).

Contextual information is very important to understand what use the species makes of these signals. Context includes everything that precedes and accompanies the signal, as well as the behavioral and physiological state of both the sender and receiver (Green & Marler 1979; Smith 1977). For example time, season, location, past experience of the receiver, etc. are all part of context. It can help the receiver to process continuous signals as categorical (Green 1975). Observation of the response(s) of the receiver to natural occurrence of the signal and/or to playback of natural or synthesized signals are also essential to assess categorical or continuous value of graded signals (Green & Marler 1979; Maurus <u>et al</u>. 1979; Byrne 1982).

OBJECTIVES

The objective of this study is to record, describe and classify the sounds produced by humpback whales in Newfoundland inshore waters. To classify whale sounds is a difficult task. Except for studies on captive odontocetes (and, under certain circumstances, wild animals, e.g., McLeod 1982), it is impossible to determine within and between individual variability. Sounds are recorded with omnidirectional hydrophones and typically, will be produced while several whales are present in the area. For the same reason, it is very difficult to get detailed contextual information and to record the receiver's response. Often, the identity of sender and receiver and even the number of animals involved in an interaction are not known. This should change soon, with the increasing use of hydrophone arrays, allowing determination of the bearing, and sometimes distance to the sound source (Watkins 1972 and 1976; Clark 1980), or when individuals are instrumented with acoustical transmitters.

One must rely almost exclusively on signals' acoustic properties in analyzing cetacean repertoires. Green & Marler (1979) mentioned that human propensity to perceive sounds categorically probably leads to labeling animal repertoires as stereotyped even when physical analysis does not fully support this jugment. Also, the physical dimensions used by the human brain to reach this result may not be those used by the animal under study. The boundaries adopted may not correspond to the natural boundaries (if any). For these reasons, Byrne (1982, p. 243) concluded:

> "Since we now know that what is a unitary call to human hearing may be a number of independent ones to the animals, and a continuum to us may be perceived as discrete categories, the many catalogues of primates (and other) calls based on human perception must of course be regarded as unreliable".

Being aware of these limitations, classification of cetacean sounds on the basis of their acoustical properties is still necessary. It would provide the necessary basic knowledge that could lead to conception of hypotheses, and later to the testing of these hypotheses. For example, it would be very hard to attempt to use playback experiments with humpback vocalizations without having at least an idea of what the different signals are. Similarly, it would be difficult to design an experiment on synthesized sounds without having previously studied their vocalizations.

A catalog of humpback sounds, even if it has to be refined as more information is gained, allows one to investigate such questions as temporal organization of sounds, seasonal variation, population differences, context of use and function, and eventually to get a better grasp on social interactions such as males competing for females in the groups described by Tyack and Whitehead (1983).

Coding of data. They are many ways to describe the acoustic properties of a sound. Early studies (e.g., Dreher 1966) resorted to human hearing: sounds categories were established upon their aural impressions on the observer. Very little quantification was possible, and the decisions about clustering sounds were arbitrary.

With the advent of sound spectrography, visual displays (frequency vs time) of sounds became available. Classification could be done using both aural and visual impressions of a signal. Quantification was relatively easy, however, the choice of parameters to measure was still arbitrary, and not necessarily relevant to the animal. Parameters frequently measured were duration, bandwidth, frequency at the beginning and end, slope, inflection points, and others (e.g., Marler 1973; Goldstein 1978; Sparling & Williams 1978; Hafner & Hafner 1979; Cleveland & Snowdon 1982; Smith et al. 1982).

However, in most studies the classification was still done by aural and visual examination of the sounds (Emmons 1978; Martindale 1980a), sometimes using such aids as playback of sounds at reduced speed (e.g., Latimer 1977; McLeod 1982). Quantitative measurements were used for descriptive statistics on the sound classes. An important problem with this classification technique is that judgment of similarity is subjective, and dependent on one's experience of classification and knowledge of the communication system under analysis (Maurus et al. 1979; Martindale 1980a). These studies are difficult to compare and repeat. Statistical analysis (often multivariate techniques) can be used, to help deciding if two classes are different or not (Cleveland & Snowdon 1982) or to check the classification and explore the relationship between classes (Hafner & Hafner 1979; Sparling & Williams 1978; Martindale 1980a).

A few studies used multivariate analyses for classification or discrimination of sounds. However, it was usually restricted to comparisons of sounds very similar to each other. For example, Smith et al. (1982) studied individual variations using one call type and five individuals. Goldstein (1978), Hafner & Hafner (1979), Thompson et al. (1979) and Martindale (1980a) studied dialectic and/or geographic variation each using a single call of a single species (two species in Hafner & Hafner 1979). These techniques help to standardize classification procedures, but can be plagued with two shortcomings: results are completely dependent on the reliability of measurements describing each sound, which are chosen arbitrarily, and results can vary greatly according to what multivariate technique is utilized. A careful classification by aural and visual impression can be better than one that is done statistically from measurements that are irrelevant to the animal.

Recently, several digitizing procedures (i.e., transformation of the spectrographic representation of a sound into a numerical representation) have been described. They have the advantage that they do not require subjective assignments of character relevance (Martindale 1980a). These methods (e.g., Bertram 1970; Miller 1979; Martindale 1980a; Clark 1982) are also better when patterns rather than descriptive measurements are to be compared, and are more appropriate when very different sound types have to be classified (Bertram 1970). However, only Clark (1982) used a statistical technique (Principal Component Analysis) to classify an animal's acoustic repertoire.

Digitizing sounds. Several methods of digitizing sounds have been reviewed and their potential for classifying humpback sounds estimated. Bertram (1970) and Miller (1979) used a grid to digitize their sounds by hand. Sounds were coded according to the squares of the grid in which energy was present. Relative amplitude was not coded. Similarity between sounds was calculated (also by hand) according to matches and mismatches of the squares representing each sound. This is extremely time consuming, but very sensitive. Adret-Hausberger (1983) used Miller's method with a few modifications. Martindale (1980a) digitized the median frequency of the fundamental of his sounds, at 15 ms intervals, with the help of a computer. As I will be discussing in the next section, many humpback sounds had no easily locatable fundamental or were broadband. Martindale's method would not be satisfactory in representing these sounds. Clark (1982) digitized the perimeter around the area of major sound energy of his sounds, using a digitizing tablet and a computer. A curvilinear regression line was then computed for each sound. This coding technique prove to be adequate in describing right whale sounds, but was not very sensitive for broadband sounds.

In this study, a new digitizing technique was devised to try to keep as much information as possible on each of the humpback sounds. Cluster analysis was then used to help with the classification process.

MATERIAL AND METHODS

STUDY AREA

Humpback whales were observed in Newfoundland's inshore waters in July and August 1979, from June to October 1980, and in April, July and August 1981. Recording was attempted at 9 locations, and sounds were produced at 6 of them (Figure 1). No sounds were recorded in 1981, but very few whales were seen: humpbacks were observed but remained silent near St. Barnards, Fortune's Bay (47°31'N, 54°59'W), in Witless Bay (47°16'N, 52°45'W) and off Torbay Pt. (47°39'N, 52°39'W). Sounds were recorded near Red Island, Placentia Bay (47°20'N, 54°10'W), Gaskiers in St.Mary's Bay (46°50'N, 53°35'W), near Chapel Arm (47°35'N, 53°40'W) and Bull Island (47°46'N, 53°48'W) in Trinity Bay, off Cape Bonavista (48°N, 53°43'W), and near Salvage (48°50'N, 53°03'W) in Bonavista Bay. Except for observations obtained off Cape Bonavista, where the distance to shore was approximately 20 km, recordings were made very close to shore (0.5-5 km).

POPULATION STUDIED

Humpback whales that feed in Newfoundland and Labrador waters are a separate substock of the northwest Atlantic population. Their number has been estimated at 1535-2720 individuals by Whitehead (1981, cited in Whitehead et al. 1982) using capture-recapture analysis. As of 1982, 1008 individuals have been identified in Newfoundland and Labrador (Katona et al. 1982).

Although some whales remain in Newfoundland waters in winter (J. Lien, pers. comm.), most of them spend the winter in Caribbean waters. They begin to arrive in Newfoundland in April, inshore sightings peaking

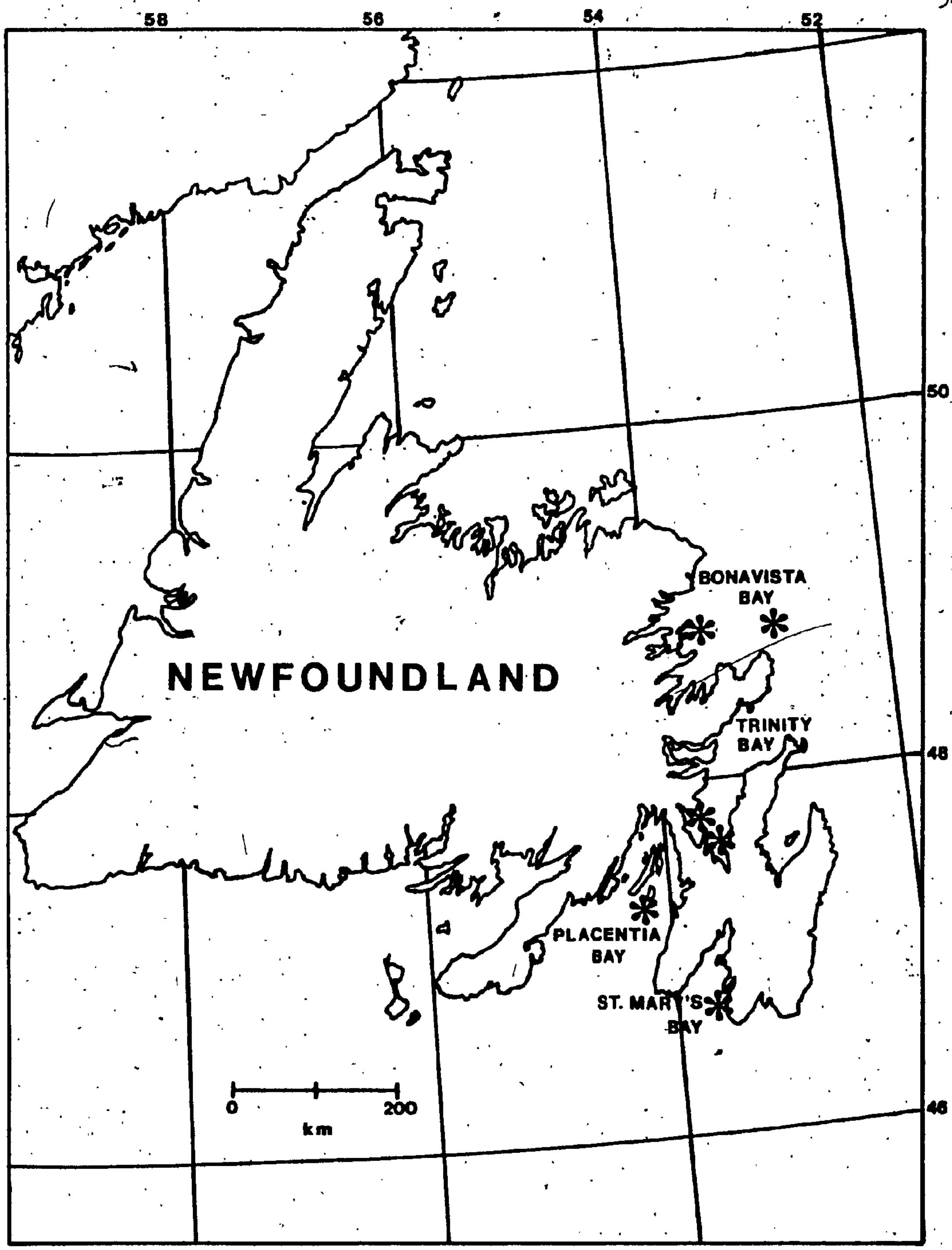

Figure 1. Map of the study area: * indicates where humpback sounds were recorded.

during capelin spawning. Whale distribution correlates with concentration of its prey species. During the summer, a northward migration takes place from the south coast to the northeast coast of Newfoundland and the Labrador coast (Whitehead et al. 1982).

RECORDING OF DATA

In 1979, 1980, and in April 1981 recordings were made from a 6 m fiberglass open boat powered by a 35 H.P. outboard engine. In July and August 1981 observations were made from the Mer D'Alors, a 9 m steel hull sailing boat. Whale sounds were recorded on one channel of a Uher 4400 Report Stereo tape recorder, using several brands of tape (Sony PR-150, Scotch 176, Scotch AV 176, or BASF LP35). All recordings were made at 19 cm/sec, using a Gould CH-17 UT omnidirectional hydrophone at a depth of approximately 10 m. At this depth, immediate surface noise and most of the disturbing effects of near surface temperature gradients are avoided, and sounds from cetaceans that are near the surface and within 1 km are usually well received (Watkins 1966). This system was flat from 20 Hz to 18 kHz. Location, date, weather conditions, species and approximate number of whales sighted, activity and position of humpbacks within 1 km of the boat were entered onto the second channel of the tape recorder.

Information collected by Memorial University's Whale Research Group was used to locate whale concentrations. The engine was stopped at about 50-200 m of the whales. If a general trend was apparent in their movement, we would try to stop the boat in front of the whales. The hydrophone was lowered and recording started. When the signal strength decreased noticeably, recording was interrupted and the boat moved closer to the whales. Because of whale movements and boat drifting, distance to the whales varied from 1-1000 m. Most of the time, whales were feeding. Recording migrating humpbacks (i.e., swimming at more than 2 knots in a straight direction) was not very successful, too much time being spent moving the boat. Often, whales stopped whatever they were doing and came to investigate the boat. Commonly, they would circle the boat a few times and resume their activities. On a few instances, they remained within 50 m for as long as 2 hrs, and our presence obviously modified their behavior. But normally, they would not pay any attention to the boat after a few minutes.

At the beginning of a session, data were recorded for a minimum of 5-10 min, and usually much longer. If the whales remained silent for this period, the "pause" phase of the recorder was used, making it possible to monitor sound production without recording. If whales started vocalizing, the tape recorder could be started within a few seconds. If other whales were in the vicinity, a whale or group would be typically monitored for 1-2 hrs (sometimes less if acoustically inactive), and then another group would be selected. All the group sizes present in an area would be observed, with a possible bias toward groups of 3 or more individuals, usually more active acoustically. However, it was often impossible to control what group and how many whales were in good acoustic range, as many groups would come and leave the vicinity of the boat when humpback density was high.

Fin and minke whales were frequently present in the working area. Sounds of the fin whale reported in the literature are of very low frequency (around 20 Hz, Payne & Webb 1971), with possible exceptions (Perkins 1966). No sounds were heard that could be attributed to fin whales during this study. All minke whales that approached the boat (always single whales) were silent. None of the sounds reported for this species (Winn & Perkins 1976; Thompson et al. 1979) were recorded during this study. Three species of odontocetes were occasionally present: the Atlantic white-sided dolphin (Lagenorhynchus acutus), the white-beaked dolphin (Lagenorhynchus albirostris) and the Atlantic pilot whale. Their click trains and squeals were readily identifiable, even at several kilometres.

I am confident that the sounds reported here were produced by humback whales. Often, sound intensity could be correlated with the distance to humpback whales. Most of these sounds were heard both in situations where only humpbacks were present and situations where other whales were in the area. These sounds were not recorded with good intensity during the few situations where all humpbacks were distant but a few other species were at close range.

Since the hydrophone was omnidirectional, it was impossible to assess with certainty what individual humpback was the source. It might have been possible when very few whales were in the area, but typically very few sounds were recorded in these situations. Even in the best of cases, only identification to the group was possible.

SPECTROGRAPHIC ANALYSIS

All tapes recorded in the field where listened to at least once. All sounds with sufficient signal-to-noise ratio were duplicated using 2 Uher 4400 Report Stereo tape recorders at 19 cm/sec. Ten working tapes containing these sounds were produced. Sound spectrographs (displaying frequency over time) were produced on a Kay Elemetrics Corp. Digital

Sona-Graph 7800 and Sona-Graph Printer 7900.

All sounds were analyzed in the 0-4 kHz scale. This scale was a compromise to get a reasonable discrimination in the low frequencies without having to use higher scales too often. It was sometimes necessary, to use the 0-8 kHz scale as well, since some sounds had most of their energy between 3 and 6 kHz.

A Uher 4400 Report Stereo tape recorder was used to input the sounds in the spectrograph for all tapes, except tape 9 and the first side of tape 5. For these 2 tapes, a Sony TC-252 and TC-270 stereo tape recorders were used. The output level of the tape recorder and the input level of the spectrograph were adjusted to keep all sounds at approximately the same level for analysis. The linear frequency scale was selected. Wide band analysis filters were used: 150 Hz in the 0-4 kHz scale and 300 Hz in the 0-8 kHz scale. Dynamic range was kept at 10 dB (LOW-zero position), to eliminate some of the background noise from the printout. This caused some loss of low intensity components. A print time of 60 sec was used.

DIGITIZING SOUNDS

Devising a technique to describe sounds. It was necessary to develop a new method of sound coding, since a large number of sounds had to be measured, and many very different patterns were obviously present. I wanted an efficient coding system that would retain as much as possible of the sounds' structure. Bertram (1970) and Miller's (1979) idea of representing each sound by a matrix was combined to Martindale (1980a) and Clark's (1982) use of a computer and digitizing tablet. I decided to systematically distribute a certain number of sampling points on the surface of a spectrogram.

Since very few sounds were longer than 2 sec, it was decided to use a matrix covering 2 sec. It means that for the few very long sounds, only the first 2 sec were coded. Each sound was described by a matrix of 16 rows and 21 columns. The 16 rows represent 16 frequencies selected from the ordinate of the spectrograms, according to a logarithmic spacing (see Appendix A). These frequencies are: 125, 164, 216, 284, 374, 492, 647, 851, 1119, 1472, 1936, 2547, 3350, 4406, 5794 and 7621 Hz. For each of these frequencies, 21 data points were distributed over 2 sec, i.e., one every 0.1 sec.

Following one of Miller's (1979) suggestions, sounds were centered horizontally in the matrix, to avoid giving too much weight to how sounds start.

The digitizing was done at the Faculty of Environmental Design (University of Calgary), with a GTCO digitizer (.001 inch accuracy) and a Digital Equipment Corp. VAX 11/750 computer, using a program in C language (see program listing in Appendix B). One plastic overlay was made for each kind of spectrogram: 0-4 and 0-8 kHz. They were both secured on the digitizing tablet. The sound to analyze was slid under the appropriate overlay and its baseline adjusted. The sound could be placed anywhere horizontally, as long as it was in the 2 sec window. Sounds longer than 2 sec where positioned as to include the first 2 sec in the window. The scale of the spectrogram (i.e., 2.5 cm/kHz and 6.115 cm/sec for a spectrogram in the 0-4 kHz range, or 1.25 cm/kHz and 12.23 cm/sec for a 0-8 kHz spectrogram) was entered in the computer, and the origin of the matrix (the (0 sec, 0 kHz) point) digitized.

The sound was played back at normal speed (and at half speed when needed) to insure that the beginning and ending of the sound were correctly assessed. A few discrete measurements were taken (see section on "Numeric data", p. 46), using the "point" mode of the digitizing tablet. These measurements allowed the computer to determine how to center the sound on the time axis. This information was displayed, and the position of the sound adjusted accordingly. The digitizer was then switched into line mode (coordinates were sent as long as the button was pushed), and the cursor passed over the sections of the 16 lines that covered the sound, with the result that the program would write a 1 in the matrix when the cursor was over one of the 336 sampling points. [1]

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[1] Although this method was developed independently, it was subsequently found similar to two other methods, which do not make use of a digitizer. Koeppl *et al.* (1978) covered sounds with a grid and scored visually each cell after the intensity of sound in contained. Rohlf & Sokal (1967) used computer cards as masks over the drawings of the organisms to be classified. Holes punched in the cards were the sampling units or cells. In their "systematic scan", the cells covered the entire image, i.e., each point of the image corresponded to one cell in the matrix. Presence of a black line through a hole was coded 1, and absence 0. Results obtained with such matrices were comparable with results from studies using more traditional measurements, like the dimensions of diverse structures on the different organisms. They also tested two methods to reduce the number of cells. One was random selection of a certain number of cells. The other was to use a lesser number of larger holes. These 3 "scanning" methods were comparable, systematic and random sampling being slightly superior.

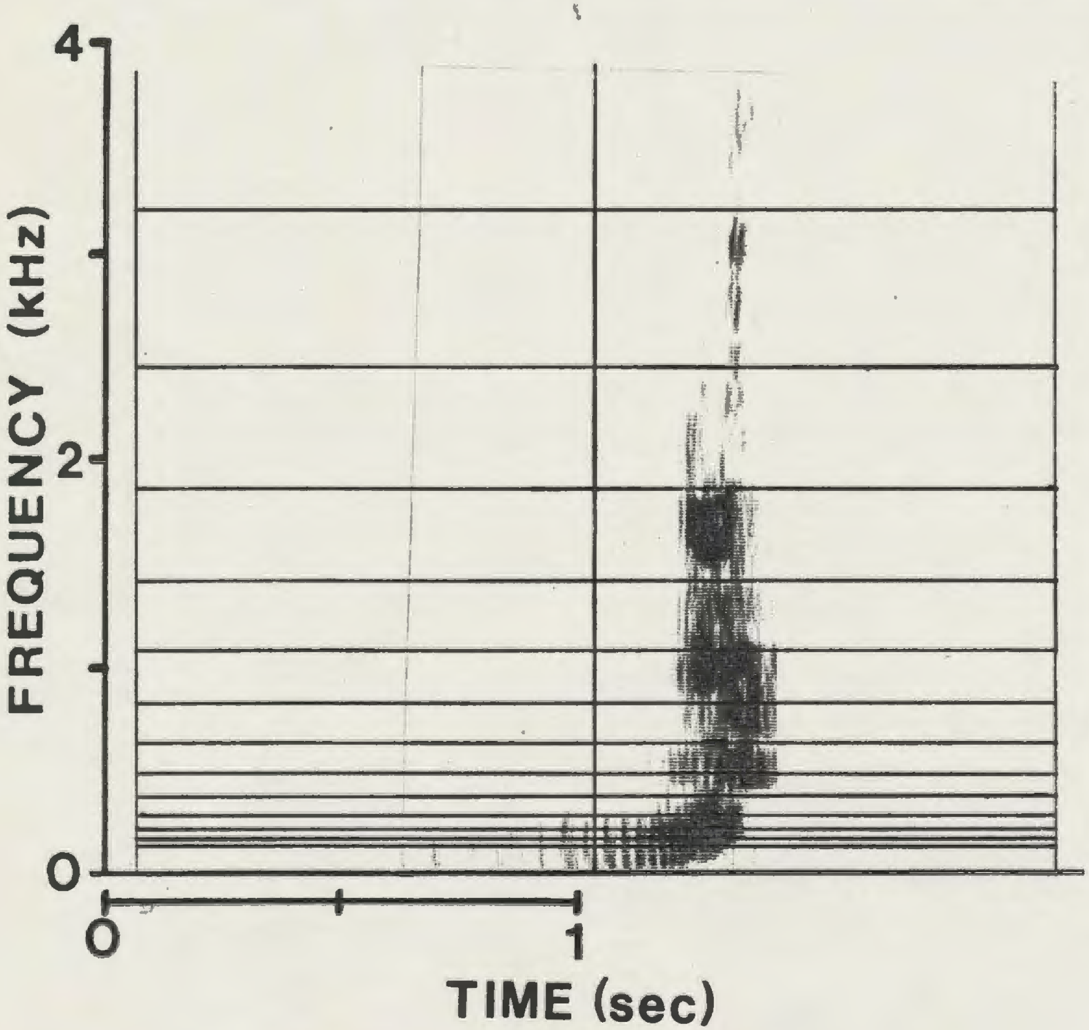
Their systematic scanning would mean to cover sounds with a complete grid of sufficiently small cells and would generate a great amount of data. Random sampling would make it difficult to check the data visually, or to estimate discrete measurements from the matrix. Increasing the size of cells would have made digitizing more difficult with the hardware that was available to me. In theory, the method used here is more closely related to random sampling, the most efficient method tested by Rohlf & Sokal (1967), than simply increasing the size of the cells to cover the entire surface of the sound.

Figure 2 illustrates a sound covered by the overlay, and the matrix that was obtained from it. It should be noted that with 0-4 kHz spectrograms, only 13 of the total 16 frequency lines were sampled, since the other 3 lines covered the frequencies above 4 kHz. For this reason, sounds analyzed in the 0-8 kHz posed a problem: the 16 frequency lines were needed, but could not be obtained from the same spectrogram. This is because the frequency scale is so compressed on a 0-8 kHz spectrogram that the 5 lowest frequency lines would not be discernible. Also, the difference in analysis filter (300 vs 150 Hz) would have made comparison of sounds analyzed in different scales fallacious. The only solution that was found to this problem was to use the 0-4 kHz spectrogram of a sound for digitizing its frequencies below 4 kHz, and the 0-8 kHz spectrogram for the frequencies above 4 kHz, and then to combine the results. This had the disadvantage of being extremely time consuming.

Conventions. The following conventions were adopted to keep data coding consistent. Pulsive sounds appear on spectrograms as a train of distinct click-like structures when the pulse rate is low enough (see the beginning of the sound in Figure 2). For this reason, the shortest units of sounds considered in this study could not be defined as continuous traces on the spectrogram. Instead, sounds that were continuous to the human ear when played in real time were the basic units, as in Payne & McVay (1971).

The discrimination of the individual clicks in some pulsive sounds also made digitizing difficult. It was difficult to remain consistent if cells were coded 0 when falling between two clicks. A slight shift of the spectrogram on the time axis could change the coding extensively.

ORIGINAL SPECTROGRAM



FREQ (Hz)	DIGITIZED MATRIX
7621	000000000000000000000
5794	000000000000010000000
4406	000000000000010000000
3350	000000000000010000000
2547	000000000000110000000
1936	000000000000110000000
1472	000000000000110000000
1119	000000000000111000000
851	000000000000111000000
647	000000000001110000000
492	000000000001111000000
374	000000000001110000000
284	000000000111110000000
216	000000011111110000000
164	000000111111110000000
125	000000111111110000000

Figure 2. Digitizing a sound. The spectrogram of the sound (left), was transformed in a matrix (16 x 21) of binary data (right) using a plastic overlay and a digitizing tablet.

Since the same sound would have appeared continuous (with side bands at intervals corresponding to the repetition rate) had a narrower analysis filter been used (see Watkins 1967b), it was decided that sampling points falling between clicks of a pulsive sound would be coded 1. However, some sounds (e.g., Figure 3) were formed of subunits so different of each other that it was not judged appropriate to score 1 in cells separating them.

Harmonics have an acoustic value and therefore should be considered when classifying sounds. For pulsive sounds, the periodicity pitch (frequency corresponding to the repetition rate of a pulsive sound) is heard in humans (Campbell 1963) and may have some value for animals as well. Also, for many humpback sounds it is at best difficult and often impossible to distinguish a fundamental frequency. This is probably not just an effect of the scales and filters used here, since a few sounds were analyzed with narrower filters and/or on a logarithmic scale, and still presented this problem. To restrict the portion of a sound that should be digitized to the dominant frequency (frequency with the highest energy, Broughton 1963) would be prone to subjective decisions when intermediate intensities are present, or when several frequencies are of the same intensity. For these reasons, all components of a sound were digitized.

A decision had to be taken for digitizing respiration sounds (blows). When blows were recorded at very close range, three parts could be recognized (Figure 4). The first part seems to correspond to noise associated with surfacing of the whale. The second part is the blow itself. The last part, rarely recorded, might represent the inhalation. For the majority of blows, parts 1 and 3 were very faint or

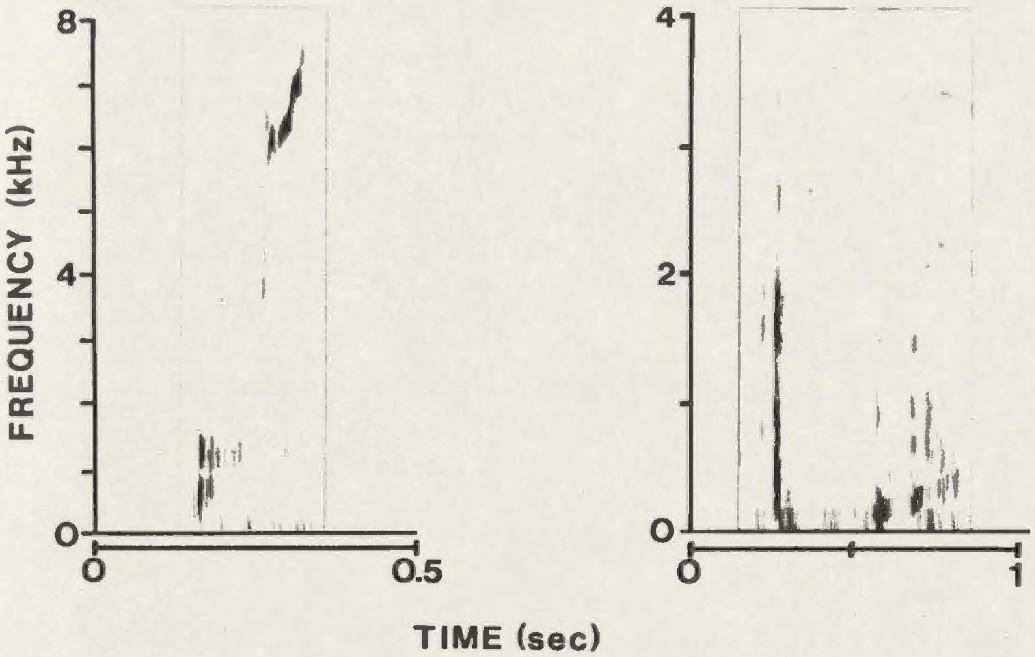


Figure 3. Two types of sounds for which the sub-units were considered too different to digitize the space between them.

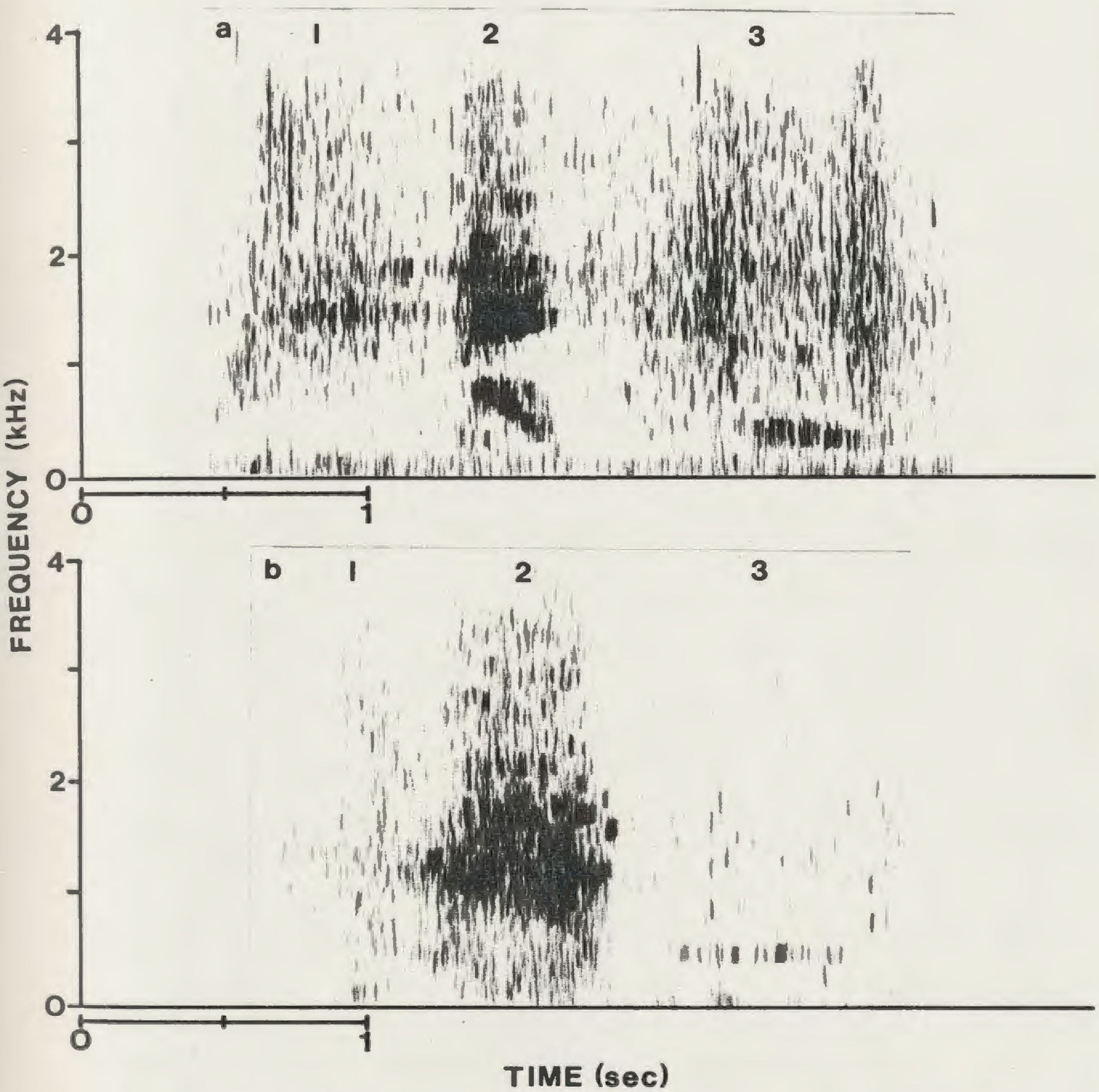


Figure 4. Two examples of whales exhalations recorded at very short distance. For each example, three parts can be distinguished. Part 1 seems to correspond to noise associated with surfacing of the whale, and maybe the beginning of the exhalation. Part 2 is the blow itself. Part 3 was rarely recorded, and might be the inhalation. Part 2 was often well recorded while the other two parts were weak or absent. For this reason, only part 2 was digitized in sounds of this type.

absent, but part 2 had a very good signal-to-noise ratio. For all sounds that could be recognized as blows, only part 2 was digitized.

Numeric data. More traditional measurements were also taken on each sound (Figure 5) to obtain descriptive statistics on the different sound types of the repertoire. This was also done with the digitizer. These variables were measured before a sound was digitized, as explained earlier. The following measurements were taken: minimum, dominant and maximum frequency at three points (at the beginning, at a visual approximation of the middle, and at the end), maximum and minimum frequencies of the sound. Duration was computed using the coordinates of the dominant frequency at the beginning and at the end of the sounds. [2] When sounds had energy below 125 Hz, 125 Hz was recorded as the minimum frequency, because low frequency noise sometimes masked the real minimum frequency.

From these measurements, additional variables were computed using the SPSS statistical package (Nie et al. 1975). These variables were the difference in dominant frequency between the beginning and the middle, the beginning and the end, and the middle and the end of the sound. Total bandwidth was also considered.

Data added to the matrix. Two sounds could have the same frequency contour but very different acoustic properties, if one was tonal and the other pulsive. Since pulsive sounds were treated as if the trace was continuous, the distinction between tonal and pulsive was not made in the matrix. Similarly, sounds that give a different aural impression and look different on spectrograms were sometimes clustered

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[2] The total duration was measured, even for those sounds lasting more than 2 sec, which were cut at 2 sec during digitizing.

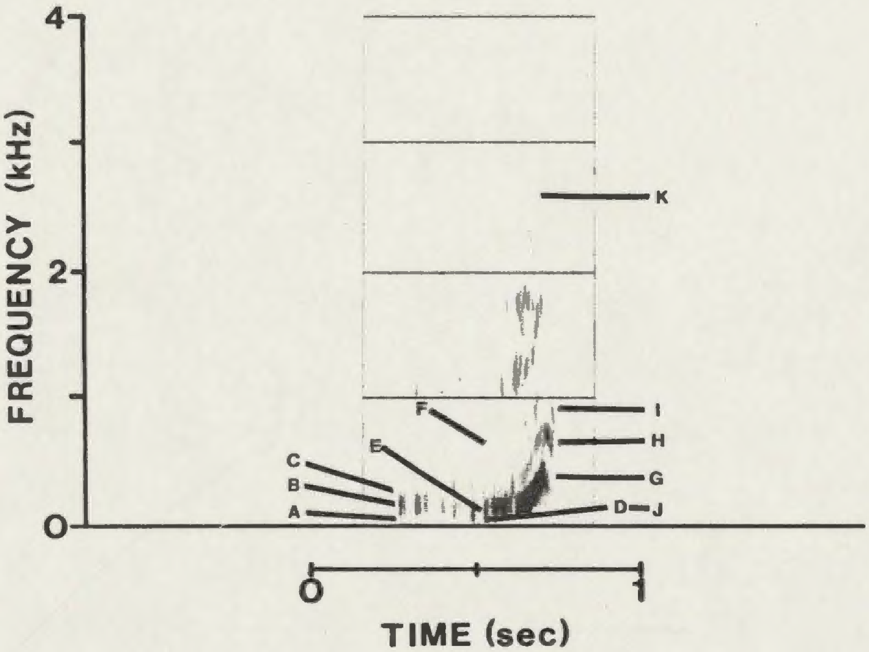

Figure 5. Other measurements taken on each sound: A minimum frequency at the beginning of sound, B peak frequency at the beginning of sound, C maximum frequency at the beginning of sound, D minimum frequency at the middle of sound, E peak frequency at the middle of sound, F maximum frequency at the middle of sound, G minimum frequency at the end of sound, H peak frequency at the end of sound, I maximum frequency at the end of sound, J minimum frequency and K maximum frequency. When minimum frequency was below 125 Hz, 125 Hz was recorded.

together in a preliminary analysis using a small subset of the data (125 cases, randomly selected). Such sounds differed in dominant frequencies, but produced very similar matrices. This is because most of the information about signal intensity was lost during digitizing. Thus additional variables were needed.

The beginning, middle and end sections of a sound were assigned 3 categorical variables (0 or 1) each to code for tonal characteristics. Information about relative sound intensity was coarsely included by computing categorical variables from the numeric data, using SPSS (Nie et al. 1975). Dummy variables were not used, because the Jaccard similarity coefficient (see the following section, Classification) does not take negative matches into consideration. These additional variables, coded 1 when the statement was true, 0 otherwise, are:

1. beginning of sound is tonal
2. beginning of sound is noisy
3. beginning of sound is pulsive
4. middle of sound is tonal
5. middle of sound is noisy
6. middle of sound is pulsive
7. end of sound is tonal
8. end of sound in noisy
9. end of sound is pulsive
10. dominant frequency at beginning of sound is 1 kHz or less
11. dominant frequency at beginning of sound is over 1 kHz
12. dominant frequency at middle of sound is 1 kHz or less
13. dominant frequency at middle of sound is over 1 kHz
14. dominant frequency at end of sound is 1 kHz or less
15. dominant frequency at end of sound is over 1 kHz
16. dominant frequency at middle is more than 100 Hz lower than at beginning
17. dominant frequency at middle is within 100 Hz of its value at beginning
18. dominant frequency at middle is more than 100 Hz higher than at beginning
19. dominant frequency at end is more than 100 Hz lower than at beginning
20. dominant frequency at end is within 100 Hz of its value at beginning
21. dominant frequency at end is more than 100 Hz higher than at beginning
22. dominant frequency at end is more than 100 Hz lower than

at middle
23. dominant frequency at end is within 100 Hz of its value at middle
24. dominant frequency at end is more than 100 Hz higher than at middle

Definitions for tonal characteristics are as in Clark (1983). A portion was tonal if it contained only harmonics that were integral multiples of the fundamental frequency; pulsive if a complex harmonic structure or individual subunits were detectable; and noisy if sound energy was distributed across a broadband of frequencies (at least 1000 Hz, in this study). Two combinations were possible for each portion of sound: noisy-tonal if wideband noise was mixed with a tonal sound; and noisy-pulsive if wideband noise was mixed with an amplitude modulated signal.

The same 125 sounds selected for the preliminary analysis were clustered again, this time with the additional variables. Since there is no external criterion (i.e. a known category structure to which to compare the resulting clusters), results were compared with a classification based on aural and visual impressions, even if such a classification is subjective. It was found that results were still better if these additional variables were given double weight (by reading them twice during cluster analysis). This was because of their relatively small number compared with the number of points in the matrix. In summary, the number of categorical variables used was 336 for the matrix and 48 (2 times 24) additional characters, for a total of 384 variables.

<u>Selection of sounds to digitize.</u> Table 2 gives the number of sounds that were digitized from each working tape. All sounds of good quality (i.e., good signal-to-noise ratio) were digitized. Seven of the ten working tapes were covered completely. Digitizing took much longer

Table 2. Contribution of each working tape and of each year to the data set.

WORKING TAPE	NUMBER OF SOUNDS ANALYZED		
	1979	1980	TOTAL
1	18		18
2	30		30
3	26		26
4	82	77	159
5	23	236	259
6		131	131
7		142	142
8		167	167
9		253	253
10		70	70
TOTAL (%)	179 (14)	1076 (86)	1255 (100)

than expected, principally because many sounds were digitized twice (on the 4 and 8 kHz scales), and the 2 parts had to be fused after digitizing. This process is almost as long as digitizing itself. For this reason, tapes 1-3 were only partially sampled. Selection was not random. Instead, the loudest sounds of the first side of each tape were selected. The number of sounds that was left can be estimated: for these 3 tapes, a mean of 25 sounds were digitized for each tape. For each of the other tapes (excluding tape 10, which was only 60% as long) an average of 185 sounds were digitized. However, I noted that there were proportionally fewer good quality sounds on the first three tapes, and estimated that less than 300 sounds were missed.

A total of 1255 sounds were digitized and used to study the humpback's repertoire. Sounds recorded in 1979 are under-represented, since they were largely contained in the first 3 tapes. They represent 14% of the total sample, while 27% of the tapes recorded in the field are from 1979. But again, the proportion of good quality sounds was lower in 1979.

CLASSIFICATION

Clustering algorithm and similarity coefficient. Humpback whale sounds were to be put in classes or clusters which properties should be "internal cohesion and external isolation" (Cormack 1971), i.e. sounds that form one class should have more in common with each other than with sounds belonging to other classes. Cluster analysis is a useful multivariate technique to explore the category structure of data, without requiring a priori knowledge of this same category structure (Anderberg 1973). There are many different algorithms performing cluster analysis, and many ways to measure similarity between sounds. Choice of both the algorithm and the similarity coefficient will affect the resulting category structure. However, even if there is no consensus on the subject, the nature of the data, the kind of classification sought, and experiments on the relative performance of algorithms and similarity coefficients can be used to select an adequate combination of clustering algorithm and similarity coefficient.

Average linkage (also called unweighted pair-group method with arithmetic averaging, or UPGMA, Sneath & Sokal 1973) was selected for the following reasons. UPGMA finds non-overlapping clusters, a desired characteristic for the classification of whale sounds. When the cophenetic coefficient is used to evaluate distortion imposed on the data by the cluster analysis, UPGMA is optimal (Boyce 1969; Sneath 1969; Farris 1969, cited in Sneath & Sokal 1973; Cormack 1971). Clifford & Stephenson (1975) found UPGMA little prone to misclassification and little group size dependent. From a visual examination of the spectrograms, graded signals were expected. However single linkage, the only algorithm used more often than UPGMA (Blashfield & Aldenderfer 1978) does not give satisfactory results if intermediates are present between clusters (Hodson *et al.* 1966, cited in Cormack 1971). UPGMA can handle this much better. Finally, in an experiment where several types of perturbations were induced in a data set of known structure, Milligan (1980) found that UPGMA performed best. Most important, it performed best in those perturbations that were likely to occur in sound digitizing: presence of noise during data measurement (it would correspond to both acoustic noise present on the spectrograms and error induced during manipulation of the digitizer's cursor) and presence of random variables

(variables that scored randomly over all classes). However, UPGMA was not optimal when outliers (objects that did not belong to any of the categories) were placed in the data set. Milligan also found that non-hierarchical algorithms (also called k-means techniques) would be the best techniques, if UPGMA was used first on the data to select the starting seeds. However, because of the number of variables used here, Clustan (see below) does not allow for a great number of clusters to be investigated, which prevented me from using k-means clustering. However, tests were made on subsets of data and did not show a great improvement over UPGMA. Appendix C explains group average cluster analysis.

I chose to use the Jaccard similarity coefficient for binary data (see Appendix C). This coefficient has the advantage of being in the 0-1 range: sounds that do not have any point in common have a similarity of 0, while identical sounds score 1. The fact that the Jaccard coefficient does not involve negative matches (i.e., cells where the sounds being compared both scored 0) is an advantage, preventing that 2 short sounds having little in common be given high similarity on the account that both had many 0s in the matrix. Also, similarity between sounds is not affected by the composition of the data set (Buser & Baroni-Urbani 1982).

<u>Cluster analysis.</u> Data storage and data manipulation were on a Honeywell DPS 8/70 computer. Data were transferred to a CDC Cyber 170/175 computer for cluster analysis. Version 2.1 of CLUSTAN (Wishart 1978 and 1982) was used to run average linkage cluster analysis. Clustan can handle a maximum of 999 sounds in a single run. It was decided to select 936 cases at random among the data set, for a first Clustan

run. [3] An APL function (listed in Appendix B) was used to select cases at random from the data set.

There was no a priori criteria for selecting the cut-off value of the similarity coefficient (e.g., minimum similarity necessary to belong to a cluster). By comparing the results of this run (called run 1) with a preliminary classification based on visual and aural impressions, it was found that sounds that look and sound very similar to the ear can have similarity values well below 0.5. However, the threshold value must not be too low either, as sounds that appeared very different to the observer would be lumped together. A value of 0.45 appeared to be a good compromise. The number of clusters obtained (97) was still fairly large. Since it was necessary to use the author's interpretation to reach the final classification, a large number of clusters was advantageous: it is easier to lump clusters that are judged identical than splitting clusters. However, some splitting was still necessary at the 0.45 level.

As suggested in Sneath & Sokal (1973), a few sounds from each cluster were selected to be run with those sounds that had been rejected for the first run. To be conservative, five sounds instead of the three suggested in Sneath & Sokal were used. These sounds selected to represent the clusters obtained in run 1 are called "seeds". The next run (run 2) contained 259 seeds and the 319 cases that had not been clustered yet, for a total of 578 cases.

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[3] A subset of 950 sounds had been selected at random, but examination of the data, it was found that for 14 cases, the possibility that 2 sounds were present simultaneously could not be ruled out. These cases were eliminated from the data set and from this first run, leaving 936 cases. The total of 1255 sounds was established after these sounds had been removed.

RESULTS

CLUSTER ANALYSIS

Clustering of the seeds in the second run. Run 1 yielded 97 clusters at the 0.45 similarity level, while run 2 produced 114 clusters. Most of the 259 seeds included in run 2 were reclustered like in run 1 (Table 3).

It can be seen that 52 sounds (20%) changed cluster between run 1 and run 2. Most of them (43 or 83%) came from clusters that were large enough (6 cases or more) to require selection at random of five seeds to represent them in run 2. The fact that random selection was used instead of taking the most representative cases of each cluster (this would have been possible with a clustering method that finds centroids, see Sneath & Sokal 1973) is probably largely responsible for the number of changes between the two runs. In other words, seeds were not necessarily representative of the majority of the cluster's members. It can be expected that such sounds, sometimes included in the cluster at values of similarity very close to the cut-off value (0.45) might be reclustered somewhere else in the second run.

Additional clustering runs. Even if the clusters revealed by both runs were largely the same, it was desirable that all sounds were assigned to only one cluster. For this reason, three supplementary cluster analysis were performed (Table 4).

In these runs, clusters in run 1 that had seeds in more than one cluster in run 2, and/or clusters in run 2 that contained seeds originating from more than one cluster in run 1, were included with all their members from both runs. Run 3 included 747 sounds coming from 27 clusters in run 1 and 25 clusters in run 2. Run 4 included 27 sounds

Table 3. Number of seeds that changed cluster in run 2, versus the number of seeds representing each cluster in run 1.

	NUMBER OF SEEDS IN CLUSTER						TOTAL
	1	2	3	4	5	6*	
NUMBER OF CLUSTERS	43	11	8	6	28	1	97
NUMBER OF SEEDS	43	22	24	24	140	6	259
NUMBER OF SEEDS THAT CHANGED CLUSTER IN RUN 2 (% IN BRACKET)	-	0	3	4	44	1	52
	-	(0)	(13)	(17)	(31)	(17)	(20)
NUMBER OF SEEDS RANDOMLY SELECTED	-	-	-	4	130	6	140
RANDOMLY CHOOSEN SEEDS THAT CHANGED CLUSTER	-	-	-	-	42	1	43
PERCENT (line 6 over line 3)	-	-	-	-	(95)	(100)	(83)
PERCENT (line 6 over line 2)	-	-	-	-	(30)	(17)	(17)

* A sixth seed was inadvertently selected in this cluster, while a cluster with four seeds should have had five seeds. Both clusters still had more seeds than what is suggested in Sneath & Sokal (1973).

Table 4. Description of the five cluster analysis runs.

RUN	CASES		NUMBER OF CLUSTERS AT 0.45 LEVEL	COPHENETIC COEFFICIENT
	NUMBER	ORIGIN		
1	936	random from total sample	97	0.78
2	578	259 seeds from run 1 319 cases left out of run 1	114	0.69
3	747	563 from 27 run 1 clusters 184 from 25 run 2 clusters	28	0.72
4	27	21 from 2 run 1 clusters 6 from 4 run 2 clusters	2	0.75
5	59	45 from 6 run 1 clusters 14 from 6 run 2 clusters	6	0.81

COMPILATION: 1255 cases (total sample size) 115 clusters from 2 clusters in run 1 and 4 clusters in run 2. Similarly, run 5 consisted of 59 sounds from 6 mingled clusters in runs 1 and 2.

Table 4 also gives the cophenetic coefficient for the five cluster analyses. This is a correlation coefficient indicative of the amount of distortion introduced in the results.

Each sound was assigned a cluster number (at level 0.45). This number comes from run 1 or 2, for those clusters that agreed perfectly between the two runs. It comes from one of runs 3 to 5 if it was necessary to go that far. Thereafter, this agglomeration of results from the five clustering runs is termed cluster analysis. In cluster analysis, the data set of 1255 sounds was divided into 115 clusters. Many clusters contained very few sounds, as only 21 clusters contained 10 sounds or more. In fact, the first 21 clusters accounted for 1049 (84%) of the 1255 sounds. Taking a lower threshold value of similarity would not solve this, as a few bad fusions (fusions of clusters considered different upon audition) occurred before these small clusters were fused to other clusters. This was found to be inherent to data coding and to the clustering algorithm (see Discussion).

DESCRIPTION OF SOUND CLASSES

An automatic method of clustering sounds, as designed here, is dependent upon the quality of data coding. Since the method used to digitize sounds was experimental, and no classification of humpback whale social sounds existed, it was necessary to check the results of cluster analysis with the only other source available: visual and aural impressions of the sounds. As stated earlier, the cut-off value of the similarity coefficient was also chosen this way.

Three levels of classification are used here to describe the humpback whale's acoustic repertoire. The first one is the CLUSTER. Clusters were obtained from cluster analysis on categorical data. The second level is the CLASS (TYPE is sometimes used interchangeably), which was obtained by comparing the clusters with the author's aural and visual impressions of the sounds. A class can correspond to a cluster, but sometimes several clusters are lumped into a single class or a cluster can be broken down into two or more classes. The third level is arbitrary and is used only to facilitate the presentation of the results. Classes that have similar general properties to the human ear are presented into GROUPS.

Some researchers simply reject all clusters containing very few cases, when they search for a number of common types to represent a sample (see Wishart 1978). Clusters that are too small are then said to be peripheral or intermediate. This convention has not been observed here, since the author was interested in finding a repertoire that was as complete as possible. Even the clusters containing only one sound were examined, to determined if it was an extreme case of an existing class, or a rare type.

Relationships between clusters, as presented in the dendrograms (graphic representation of the clustering process), were not taken into account because of the distortion inevitably included into a two-dimensional representation of the results, chiefly at such a high level of fusion (Sparling & Williams 1978). Cluster analysis was only used to divide the data set into clusters and to list the members of each cluster. The author numbered the clusters to facilitate presentation of the results.

Statistics on clusters (Appendix D) included all sounds belonging to each cluster, even if many classes were represented. Similarly, statistics on classes were computed using all sounds composing the class, even if they came from different clusters.

Martindale (1980b) emphasized the fact that cluster analysis does not give the reasons for the splitting of the sample in a certain number of clusters. A difference in duration, frequency, or in the value of any other measured variable between two clusters must not be seen as the reason for the grouping, and still less as a significant difference between the two clusters. However, the reasons for the grouping in different clusters can often be deduced from these differences, chiefly with the similarity coefficient used here (Appendix B), since it depends on the number of matches and mismatches between sounds. Variations in duration will increase the number of mismatches; more so in low frequencies, because of the logarithmic scale. Bandwidth, minimum frequency, and maximum frequency also have obvious effects on the computation of similarity coefficients. Amplitude will have little effect, since it was poorly represented in the measurements. When differences between clusters are mentioned in the presentation of the sound classes, they were deduced from each cluster's properties.

A coding of cluster types was developed to evaluate the success with which cluster analysis recognized the different classes of the repertoire. This coding was based on the proportion of a class which was included in a given cluster, and on the proportion of the cluster made up by this class (Table 5). Clusters that had at least 50% of their cases in one class, and which contained at least 50% of the elements of the class, were of type "A" relative to this class. Type "B" and "C" clusters also had at least 50% of their elements in the same class, but accounted for only 25-49% and less than 25% of the class, respectively. Type "D" clusters had between 25-49%, and type "E" less than 25% of their elements belonging to one class, but both accounted for 50% or more of the class. Finally, a cluster was said to be of type "F" relative to a class if less than 50% of its elements were of this class, while less than 50% of the class originated in this cluster.

This code was used as an index of the success of cluster analysis in the following manner. The less interpretation necessary to define a sound class, the better the success of cluster analysis in recognizing this class. Accordingly, a class that contained a type A cluster was very well recognized by cluster analysis: the author's impressions were that most sounds in this cluster were more similar to each other than to sounds of other clusters. A class which had a type "B" cluster was still well recognized by cluster analysis, since one cluster was almost entirely devoted to it, accounting for a good proportion of the class. Internal homogeneity was good, but external isolation not complete. Classes that did not have better than type "C" clusters were usually split in many clusters. Internal cohesion was still very good, but external isolation poor. Cluster analysis did poorly with classes characterized only by a type "D" cluster, since they were placed with many sounds belonging to other(s) class(es). Much interpretation was needed to delimit these classes, as both internal cohesion and external isolation were poor. Classes characterized by type "E" or "F" clusters were not recognized at all by cluster analysis. Internal cohesion and external isolation were very poor. The distinction between the two was

Table 5. Description of the cluster types used in evaluating the relative success of cluster analysis for each class.

PERCENT OF CLUSTER ATTRIBUTED TO THE CLASS	PERCENT OF CLASS IN A GIVEN CLUSTER		
	>49%	25-49%	<25%
>49%	A	B	C
25-49%	D	F	F
<25%	E	F	F

that most or all the members of the class were included in the same cluster in type "E", because it was usually a very small class (i.e., rare type).

By considering the highest type reached by a cluster, it is possible to visualize what role it played in the classification process (Table 6). Among the 115 clusters, 31 were very easy to interpret: most of their cases were very similar to each other, and not many such sounds were found in other clusters. Seventy-five clusters were small and contained sounds similar to each other. However, the author was able to find a relatively high proportion of the same sounds in other clusters. Often, many type "C" clusters were fused together by the author. Only nine clusters were useless: they contained many different sounds, but only a few cases of each.

By comparing the results of cluster analysis with his aural and visual impressions, the author recognized 50 sound classes. Table 7 gives the relative success of cluster analysis in recognizing these classes. Success depended partially on class size, as indicated in the last column of Table 7: by considering only those classes that have five cases or more, one can see that 15 out of 28 classes were relatively well recognized by cluster analysis, while another 10 were recognized, but not well delimited: they were split in a variable number of small clusters. Only three classes with at least five cases were not discriminated at all by cluster analysis.

Table 6. Highest "type" obtained for each cluster.

CLUSTER TYPE	SUCCESS OF CLUSTER ANALYSIS	NUMBER OF CLUSTERS
A	very good	12
B	good	18
C	had to be fused with other clusters	76
D	poor	1
E	very poor	3
F	very poor	5
TOTAL		115

Table 7. Number of classes characterized by each cluster type.

CLUSTER TYPE	SUCCESS OF CLUSTER ANALYSIS	NUMBER OF CLASSES	NUMBER OF CLASSES WITH AT LEAST 5 CASES
A	very good	12	8
B	good	10	6
C	interpretation needed	10	10
D	poor	2	0
E	very poor	14	2
F	very poor	2	1
TOTAL		50	27

GROUP 1.

Three classes belonged to group 1 (Table 8). In general, these sounds lasted more than 0.5 sec, had a large amount of noise, and a bandwidth of over 4 kHz. They typically had little energy below 400 Hz. A band of dominant frequency was present and, except for class 1c, was tonal and frequency modulated.

Class 1a. These sounds had little energy below 0.4 kHz, although the minimum frequency averaged 0.22 kHz (Table 8). They had a strong tonal component (Figure 6), shaped like an inverted "U": frequency rose in the first third of the sound, then decreased below the initial frequency by the end of the sound. This high energy component rarely went over 1 kHz, and the peak frequency at the beginning, middle and end of the sound averaged 0.79, 0.84, and 0.63 kHz respectively. Above this component, much noise was present, reaching a mean maximum frequency of 4.85 kHz. The mean duration was 0.62 sec and the average bandwidth 4.63 kHz.

This was the fourth largest class in the repertoire, with 100 cases. It can be seen in Table 8 that class 1a was well discriminated by cluster analysis, with 85% of its cases coming from cluster 1, accounting for 98.8% of the cluster's members. The few cases that were clustered in other clusters appeared to be extreme cases in the class, mainly in duration and amount of noise (bandwidth). While mean duration was 0.61 sec in cluster 1, it was only 0.19 sec in cluster 49 (which contained 1 class 1a sound), 0.31 sec in cluster 2 (with four of its eleven members in class 1a) and 0.49 sec in cluster 75 (one of its two members was of this class), but as much as 0.85 sec in cluster 8 (with one out of five cases in this class) and 1.02 sec in cluster 3 (where

Table 8. Characteristics and clustering of the three classes in Group 1.

For each class, the number of cases (n), mean dominant frequency at three points (start, middle, and end of sound), minimum and maximum frequencies, and duration are given, with the standard deviation in brackets. Structure of the sounds and the number of clusters of each type are also shown. The highest proportion (%) of the class found in a single cluster is in brackets, below the appropriate cluster type.

CLASS (n)	DOMINANT FREQ (kHz) START	MIDDLE	END	MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)	STRUCTURE *	CLUSTER TYPE ** A	B	C	D	E	F
1a	0.79	0.84	0.63	0.22	4.85	0.62	TN	1		1			4
(100)	(0.51)	(0.28)	(0.51)	(0.11)	(1.51)	(0.17)		(85)					
1b	1.29	1.42	1.15	0.44	5.88	1.08	TN	1		3			
(34)	(0.43)	(0.68)	(0.72)	(0.18)	(1.72)	(0.24)		(85)					
1c	1.63	1.11	1.83	0.65	7.42	1.52	FN					1	
(1)	-	-	-	-	-	-						(100)	

* Structure can be tonal (T), noisy (N), pulsive at a slow (S) or fast (F) repetition rate, and presence of harmonics (H). Repetition rate was slow if the individual sub-units could be distinguished with an analysis filter of 150 Hz. Conditions that applied to many but not all cases are in brackets.

** Cluster types are described in Table 5, p. 62.

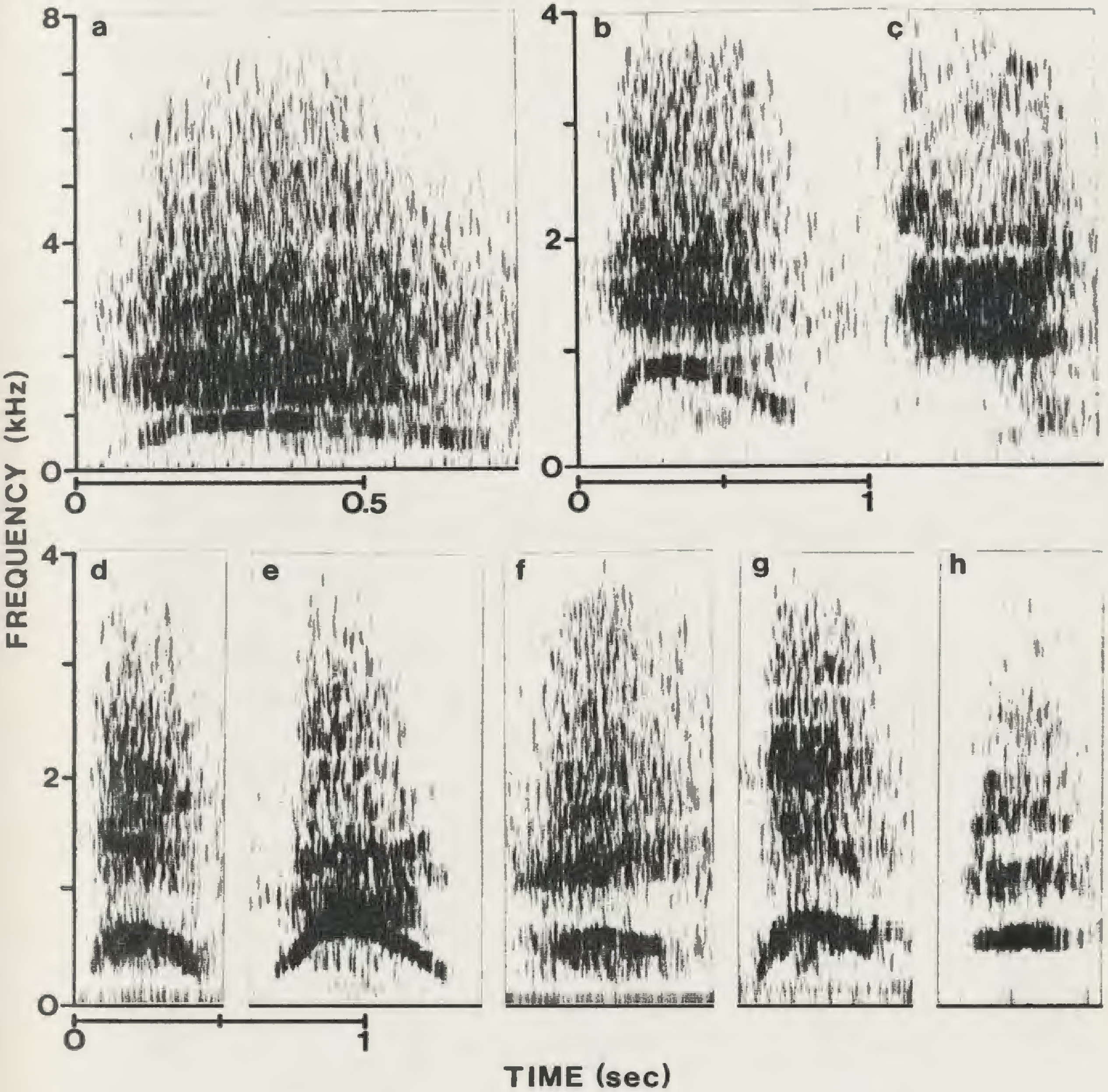


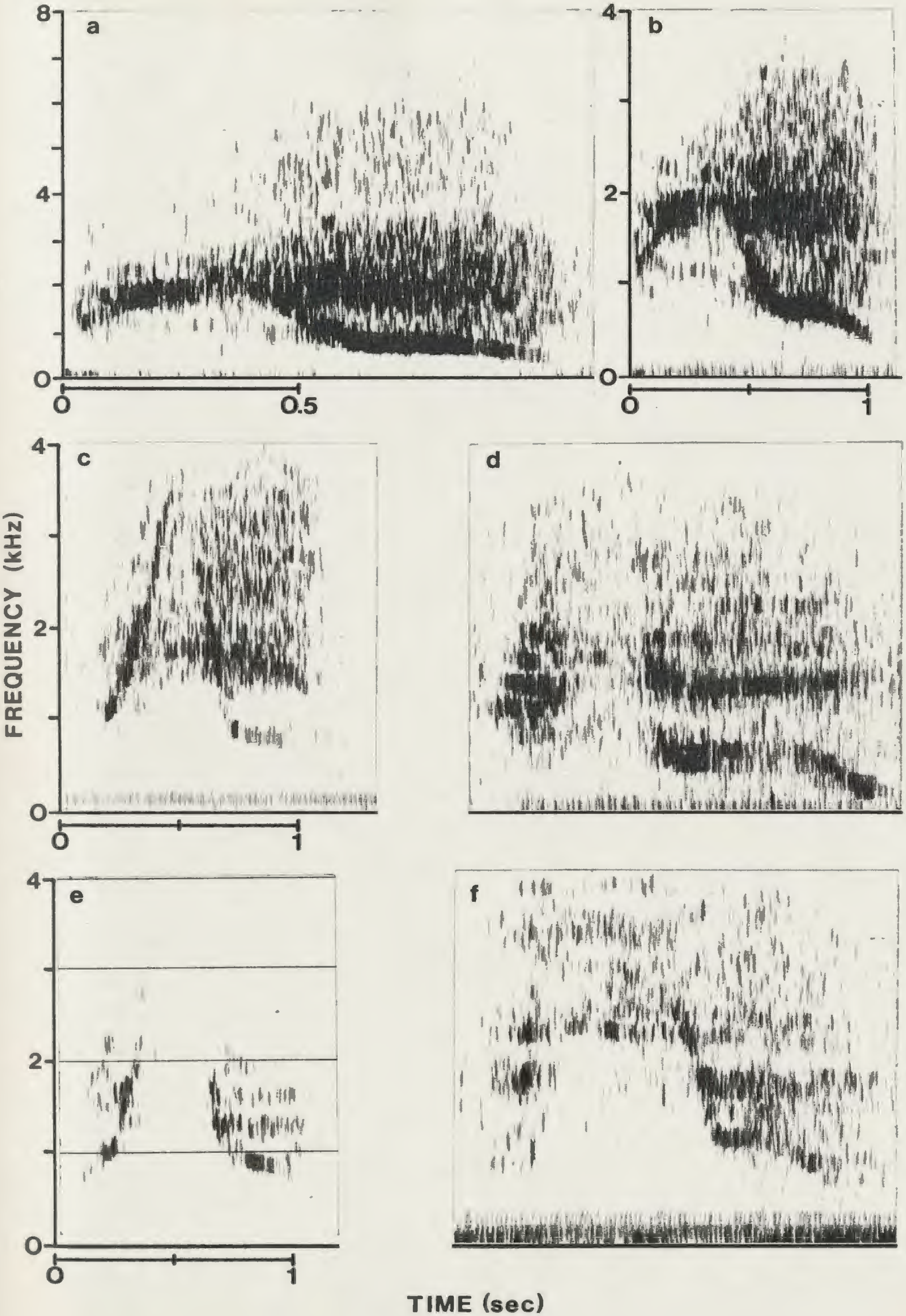
Figure 6. Some spectrograms of class 1a sounds. a and b are the same sound. a-c are from cluster 3; d-g are from cluster 1; h is from cluster 2. The abscissa is broken when two sounds come from different spectrograms or when the interval between them has been shortened. The analysis filter is 150 Hz and 300 Hz for the 0-4 kHz and 0-8 kHz spectrograms, respectively.

seven out of 36 cases were identified as class 1a). Bandwidth was 4.45 kHz in cluster 1, but only 2.80 and 3.90 kHz in clusters 75 and 2 respectively, and as much as 4.89, 5.60 and 7.03 kHz in clusters 49, 3 and 8. Dominant frequency was also higher in clusters 3, 8 and 49 than in cluster 1 (see Appendix D for statistics on clusters).

Class 1b. On average, sounds of this class were longer (1.08 sec) and broader (5.44 kHz) than those of class 1a (Table 8), and with less energy in low frequencies: minimum frequency was 0.44 kHz, and peak frequency was 1.29 kHz at the beginning, 1.42 at the middle, and 1.15 at the end (Table 8 and Figure 7). They also differed from sounds of the previous class by the much sharper peak frequency increase at the beginning: it usually reached 2 kHz or higher. Peak frequency was usually back below its original level slightly after the middle of the sound. Class 1b sounds also had high frequency noise reaching in average 5.88 kHz.

Thirty-four sounds were identified in class 1b, which ranked tenth overall in size. Cluster 3 contributed 85.3% of them, and had only 19.4% of its members in other classes. Thus it was a type "A" cluster, which means that class 1b was well discriminated by cluster analysis. Clusters 4 and 5, with one sound each, were found to be class 1b sounds lacking most of the noise usually present in this class (Figure 7e), resulting in narrower bandwidth (2.9 and 2.14 kHz respectively, against 5.6 in cluster 3). The lack of noise suggests that these two sounds were produced at a distance, which could also explain the break occurring in middle of cluster 4 sound (Figure 7e). This sound was also exceptional in having its frequency downsweep nearer the end. Cluster 6 was a small cluster of six sounds, three of which being class 1b sounds

Figure 7. Some spectrograms of class 1b sounds. a and b are the same sound. a-d are from cluster 3; e is from cluster 4; f is from cluster 6. Analysis filter is as in Figure 6, p. 67.


a
b
c
d
e
f
8
4
0
0.5
2
1
FREQUENCY (kHz)
TIME (sec)

of longer duration than usual (Figure 7f): mean duration was 1.52 sec in cluster 6, while only 1.02, 0.98 and 0.80 sec in clusters 3, 4 and 5 respectively. Peak frequency was in the 2-2.3 kHz range, which is almost 1 kHz above the values in cluster 3. Noise reached 7.81 kHz, for a bandwidth of 7.14 kHz. Sounds of this cluster also had little energy below 2 kHz.

With sounds of class 4b, that will be described later, sounds of classes 1a and 1b were the only ones that could be correlated with whales' behavior with the equipment used in this study. These sounds could readily be assigned as humpback blows. More specifically, class 1a sounds were normal blows, while sounds of class 1b corresponded to the wheezing blows described by Watkins (1967a). Class 1b sounds could be heard at greater distance underwater than normal blows.

Class 1c. This sound was pulsive (Figure 8), with most of its energy in two bands around 1.1 and 1.7 kHz. Its duration was 1.52 sec and its bandwidth 6.77 kHz (Table 8). Unlike the beginning, the end was abrupt. The peak frequency was 1.63, 1.11 and 1.83 kHz at the 3 usual points. However, this did not represent frequency modulation, as can be seen in Figure 8. The second band of high energy simply began before and ended after the lower band. This class had only one case. Once digitized, it was very similar to the longest of class 1b sounds, and was put with them in cluster 6, where it accounted for only 16.7% of the cluster.

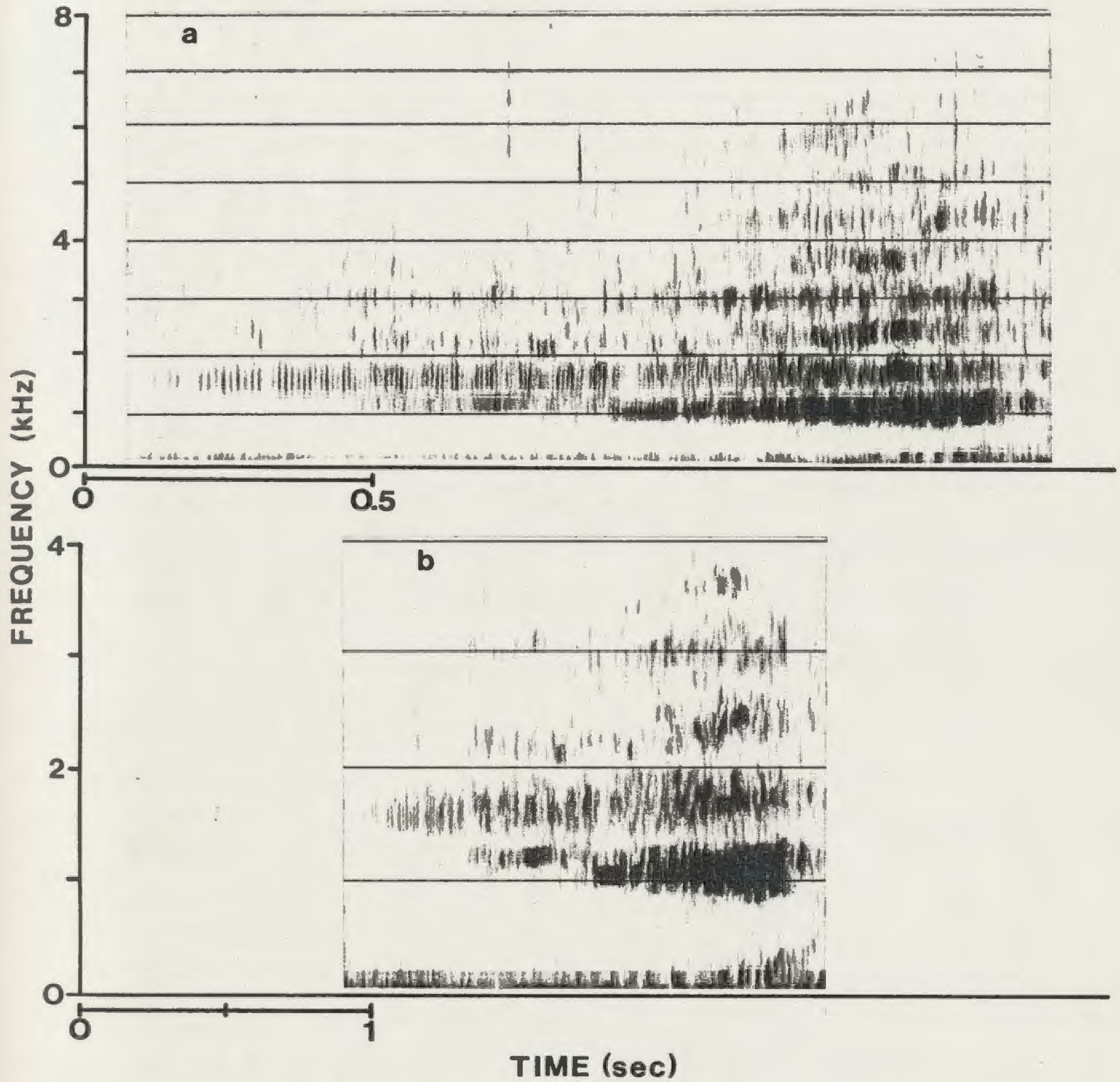


Figure 8. Spectrograms of class 1c sound. Low frequency background noise is apparent in the 0-100 Hz region of b. Analysis filter is as in Figure 6.

GROUP 2.

These sounds were tonal, and except for one class, had a rich harmonic structure and strong frequency modulation. They were of long duration, the shortest mean duration being 0.6 sec. Nine classes were included in this group. They had few low frequencies, and their minimum frequency were usually around 0.5 kHz (Table 9).

Class 2a. These sounds were long (mean of 1.39 sec, Table 9) and tonal, with 3-9 harmonics (Figure 9), resulting in a mean bandwidth of 7.07 kHz. They were also characterized by a very marked frequency modulation (up, down and then about constant). This was not shown in the summary statistics for this class, the three measurements of peak frequency being 1.84, 0.87 and 1.08 kHz. This is because the up-down modulation was produced in the first half of the sound, like in wheezing blows, and not sampled by the discrete measurements. Minimum and maximum frequencies were 0.55 and 7.62 kHz respectively.

This class had three sounds, ranking thirty-third in size. It was best discriminated by a type "B" cluster: cluster 7, with a single element (type "B"). The two other cases came from cluster 8, which had five elements. The class was probably split because of differences in duration: 1.72 sec in cluster 7, and 0.85 sec in cluster 8. The other characteristics of these two clusters were very similar (Appendix D).

Class 2b. This class was similar to the previous one. It was tonal, and two to over four harmonics were present (Figure 10). However, it was shorter (mean duration of 0.85 sec, Table 9) and the bandwidth narrower (4.99 kHz). Minimum frequency was 0.69 kHz, while maximum frequency was 5.68 kHz. Peak frequency measurements were 2.50, 1.35 and 2.00 kHz, which did not reflect the shape of the fundamental

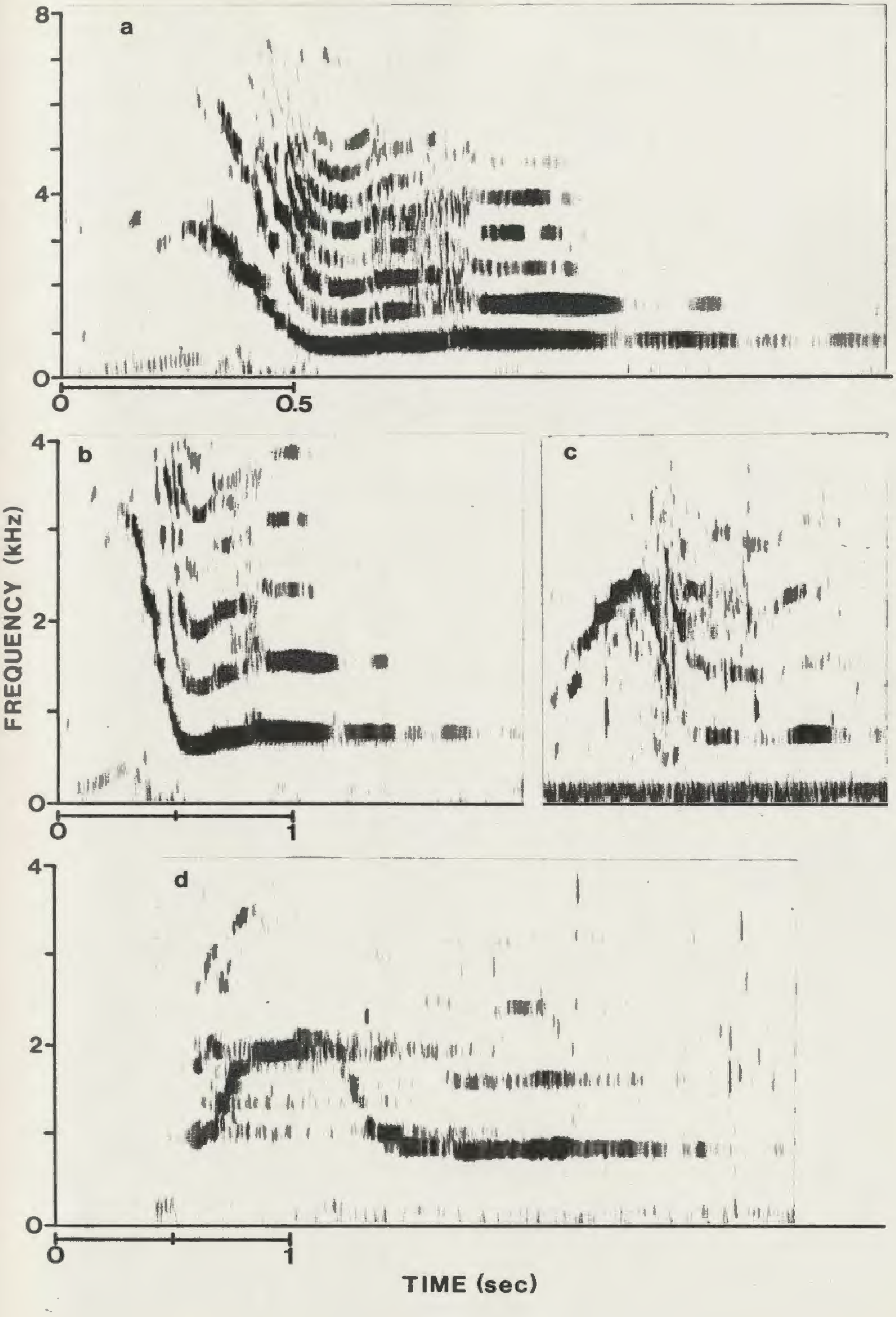
Table 9. Characteristics and clustering of the nine classes of Group 2.

For each class, the number of cases (n), mean dominant frequency at three points (start, middle, and end of sound), minimum and maximum frequencies, and duration are given, with the standard deviation in brackets. Structure of the sounds and the number of clusters of each type are also shown. The highest proportion (%) of the class found in a single cluster is in brackets, below the appropriate cluster type.

CLASS (n)	DOMINANT FREQ (kHz) START	MIDDLE	END	MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)	STRUCTURE *	CLUSTER TYPE ** A	B	C	D	E	F
2a (3)	1.84 (1.32)	0.87 (0.18)	1.08 (0.46)	0.55 (0.14)	7.62 (0.15)	1.39 (0.34)	TH		1		1 (67)		
2b (4)	2.36 (0.63)	1.30 (0.62)	2.00 (0.44)	0.69 (0.18)	5.68 (1.98)	0.85 (0.26)	TH		2 (25)				2
2c (1)	1.53 -	0.77 -	1.51 -	0.66 -	2.52 -	1.59 -	TH	1 (100)					
2d (3)	1.43 (0.15)	1.62 (0.17)	1.64 (0.15)	1.13 (0.19)	2.56 (0.85)	0.73 (0.12)	T(H)					1 (67)	1
2e (4)	0.82 (0.20)	0.83 (0.07)	0.68 (0.22)	0.49 (0.15)	2.30 (0.50)	1.85 (0.37)	TH	1 (75)	1				
2f (15)	1.34 (0.78)	1.01 (0.67)	1.49 (1.13)	0.49 (0.16)	7.17 (0.85)	0.85 (0.34)	TH(F)			12 (13)			2
2g (12)	1.39 (0.95)	1.66 (1.10)	2.32 (1.27)	0.45 (0.22)	6.71 (1.61)	0.63 (0.33)	TH		1 (25)	5			2
2h (4)	1.00 (0.42)	1.23 (0.23)	1.73 (0.14)	0.71 (0.12)	3.07 (1.39)	0.82 (0.43)	T(HF)		3 (25)				1
2i (4)	2.58 (2.18)	2.62 (1.14)	2.13 (1.69)	0.80 (0.35)	5.45 (2.92)	0.60 (0.38)	TH(F)		3 (25)				1 (25)

* Structure types are as in Table 6, p. 64.
** Cluster types are described in Table 5, p. 62.

Figure 9. Spectrograms of class 2a sounds. a and b are the same sound. a-c are from cluster 8; d is from cluster 7. Analysis filter and breaks in abscissa are as in Figure 6, p. 67.


a
b
c
d
8
4
0
2
FREQUENCY (kHz)
0
0.5
1
TIME (sec)

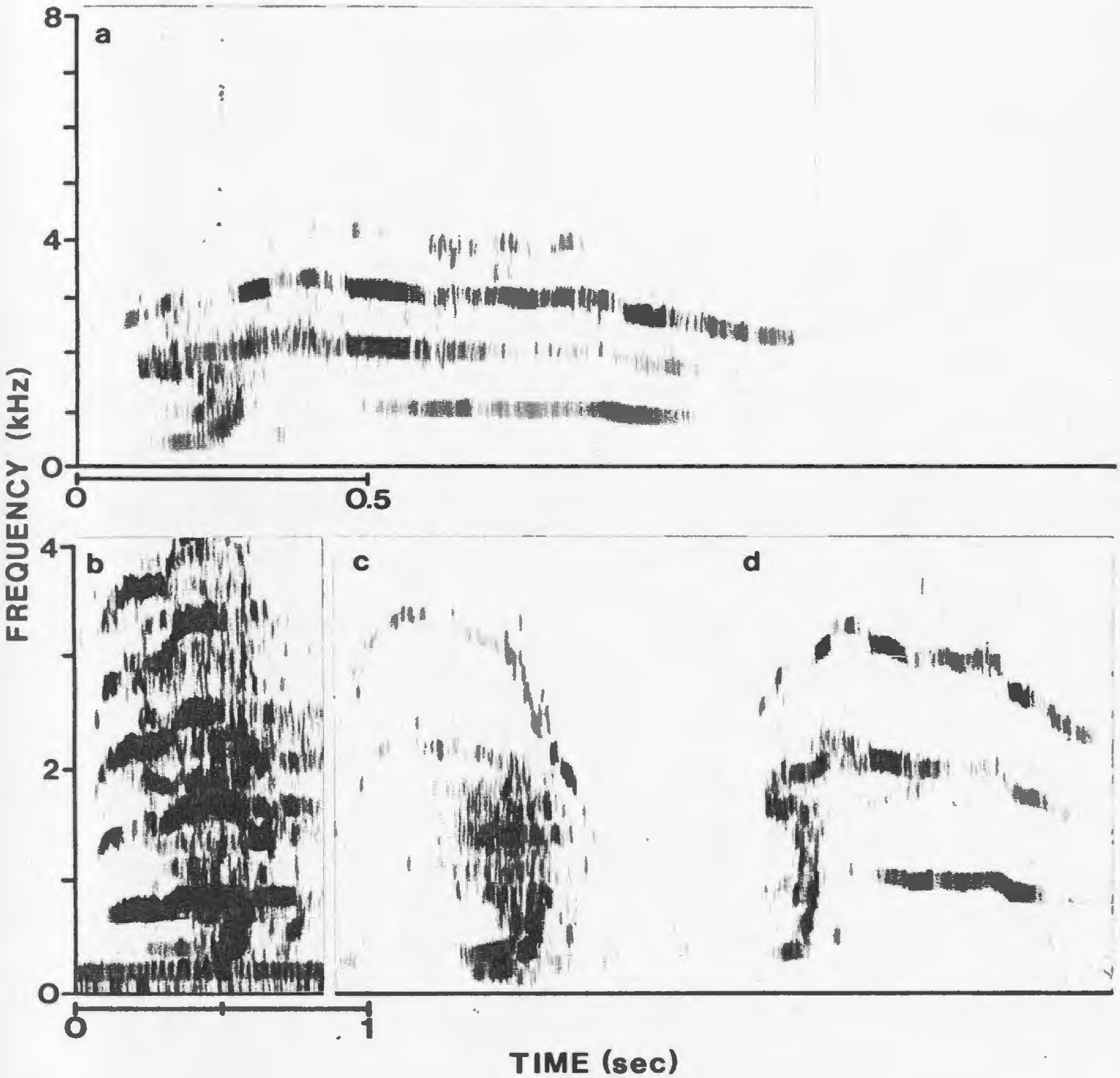


Figure 10. Some spectrograms of class 2b sounds. a and d are the same sound, from cluster 10; b is from cluster 8; c is from cluster 9. In all cases, another sound can be seen in the lower frequencies (class 7c). Analysis filter and breaks in abscissa are as in Figure 6.

frequency (an inverted "U"), for the reason given above: the fundamental of some sounds could be shorter than some harmonics. Consequently, the measurement of peak frequency for the beginning or the end was not done on the same harmonic than the measurement at the middle. It should be noted in Figure 10 that two sounds are superposed in the three examples given. However, tonal class 2b sounds with their harmonics are easily discriminated.

Class 2b had four members, and was the twenty-eighth largest in the data set. It was characterized by two type "B" clusters: clusters 9 and 10, with one element each. These two clusters were fused during audition because of their very similar acoustic properties. Duration was 0.76 sec in cluster 9, and 1.19 sec in cluster 10, which might explain why they were not clustered together. Another case was found in each of clusters 8 and 81. Lower fundamental frequencies, and for the sound in cluster 8, a wider bandwidth (7.03 kHz, compared with 3.09 and 3.68 in clusters 9 and 10 respectively) are possible reasons for this splitting. Also, sounds with similar shape but different frequencies, chiefly when made up of narrow frequency bands, were given low similarities with the Jaccard coefficient, because of the few matches between them (see Discussion).

<u>Class 2c.</u> This class was tonal, but the first harmonic was much louder than the fundamental (Figure 11). Frequency modulation was conspicuous: the frequency first went down for a short moment, then went up and down twice, although the rate of frequency change was much lower the second time. It lasted 1.59 sec (Table 9) and had a limited bandwidth (1.86 kHz). Peak frequency measurements were 1.53, 0.77 and 1.51 kHz. The second measurement, much lower, was in fact taken on the fundamen-

tal, quite loud in this part of the sound. Minimum and maximum frequencies were 0.66 and 2.52 kHz respectively.

This class had a single element, and has been isolated both by cluster analysis and by aural and visual impressions: cluster 11 contained only this sound.

Class 2d. The frequency of these tones was constant, as can be seen from the peak frequency measurements: 1.43, 1.62 and 1.64 kHz (Table 9). Only a very faint harmonic was sometimes noticeable (Figure 12a). The case illustrated in Figure 12 c was superposed on a sound of another type, but was easily discriminated from it. Mean duration was 0.73 sec and bandwidth 1.43 kHz. Minimum and maximum frequencies averaged 1.13 and 2.56 kHz respectively.

This class had 3 cases, and ranked thirty-third, with three other classes of this size. It was not recognized by cluster analysis, being characterized by a cluster of type "E" and another of type "F". Two (67%) cases were found in cluster 41, which contained mostly class 3c sounds, that will be described later. The third one was found in cluster 53, which contained mostly class 5b sounds. In both cases they were out of place, being among much shorter sounds: mean duration was 0.07 and 0.17 sec in these two clusters. The importance of this class might have been underestimated: some cases had not been digitized for many reasons (too much echo, masked by other sounds, or thought to be poor recordings of wheezing blows).

Class 2e. These sounds were tonal, though some amplitude modulation was sometimes present (Figure 13). They had one or two harmonics. In two cases, side bands were present for a short time, but it was not clear if they were caused by the simultaneous emission of a second tone,

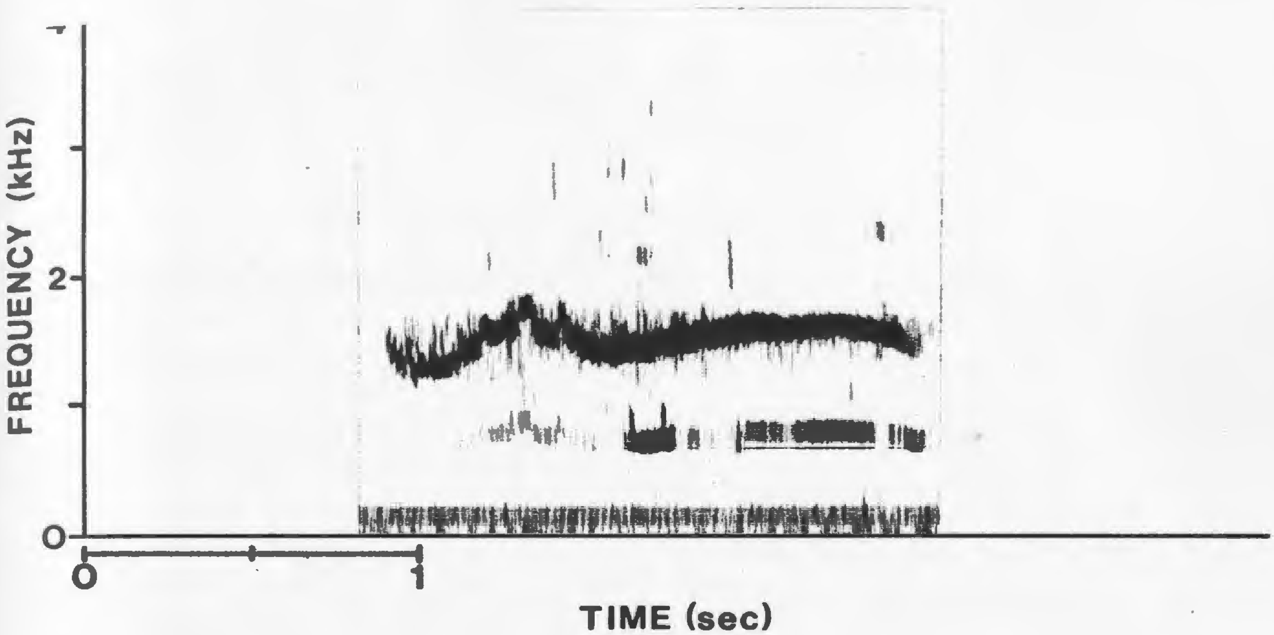


Figure 11. Spectrogram of class 2c sound. Analysis filter is as in Figure 6 p 67.

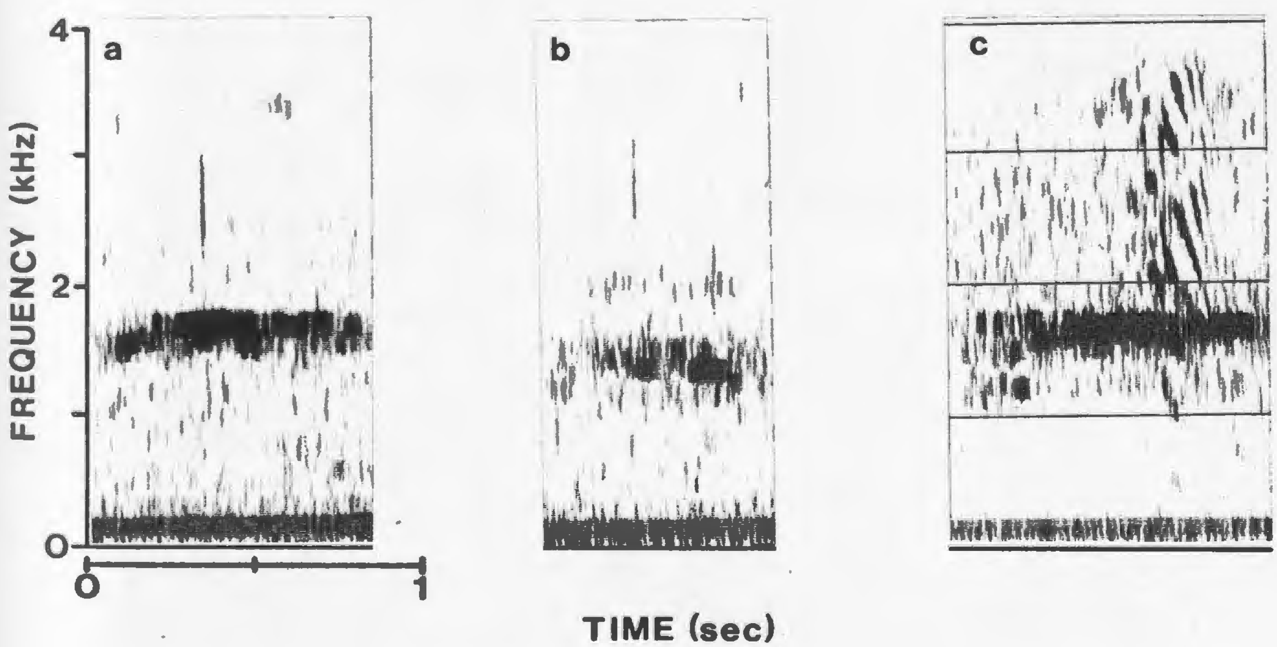
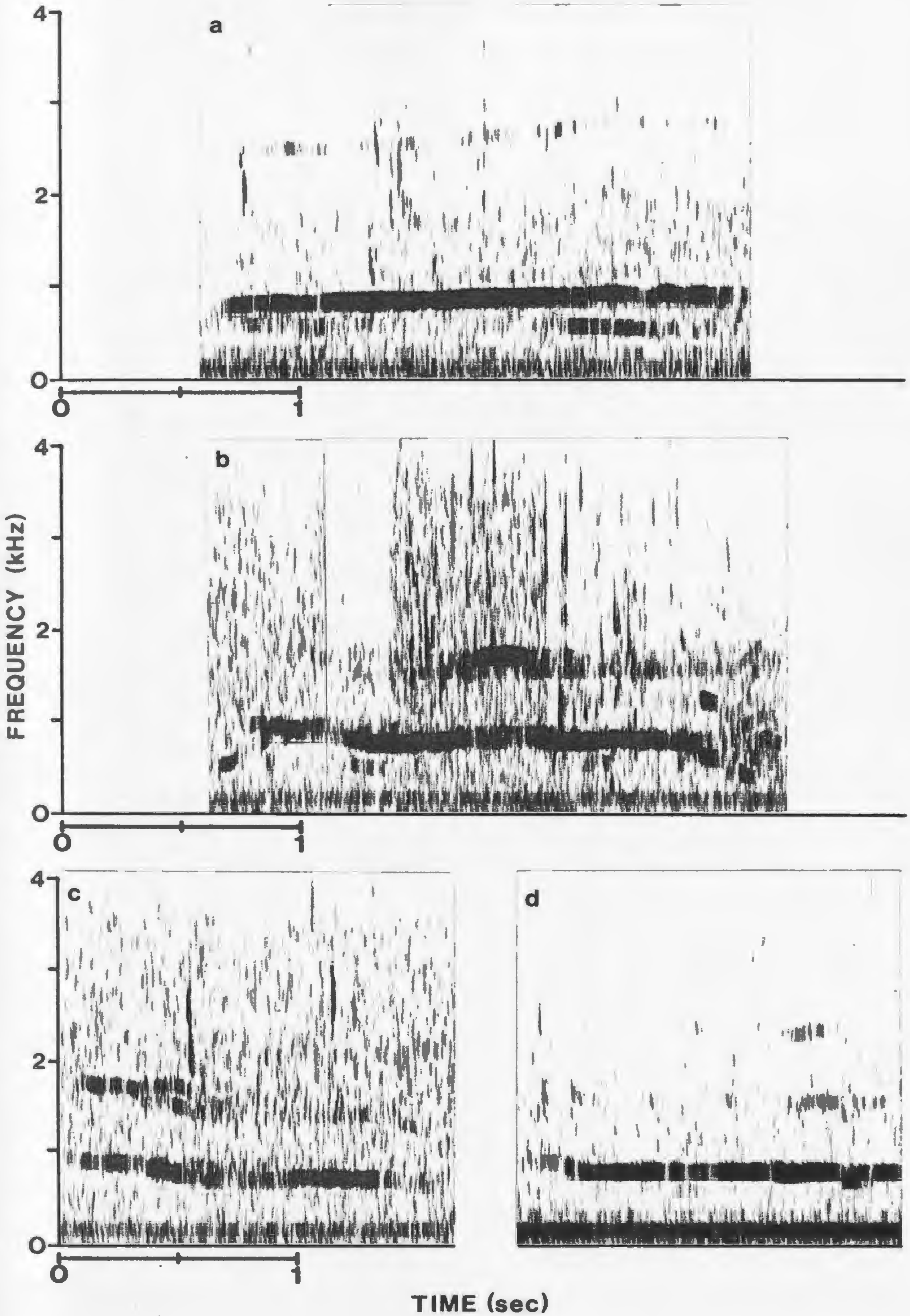


Figure 12. Spectrograms of class 2d sounds. a and c are from cluster 41. b is from cluster 53. A second sound (class 13a) is present in c. Analysis filter and breaks in abscissa are as in Figure 6 p 67.

Figure 13. Spectrograms of class 2e sounds. a, b and d are from cluster 13; c is from cluster 12. Analysis filter and breaks in abscissa are as in Figure 6, p. 67.


a
b
c
d
4
2
0
0
1
FREQUENCY (kHz)
TIME (sec)

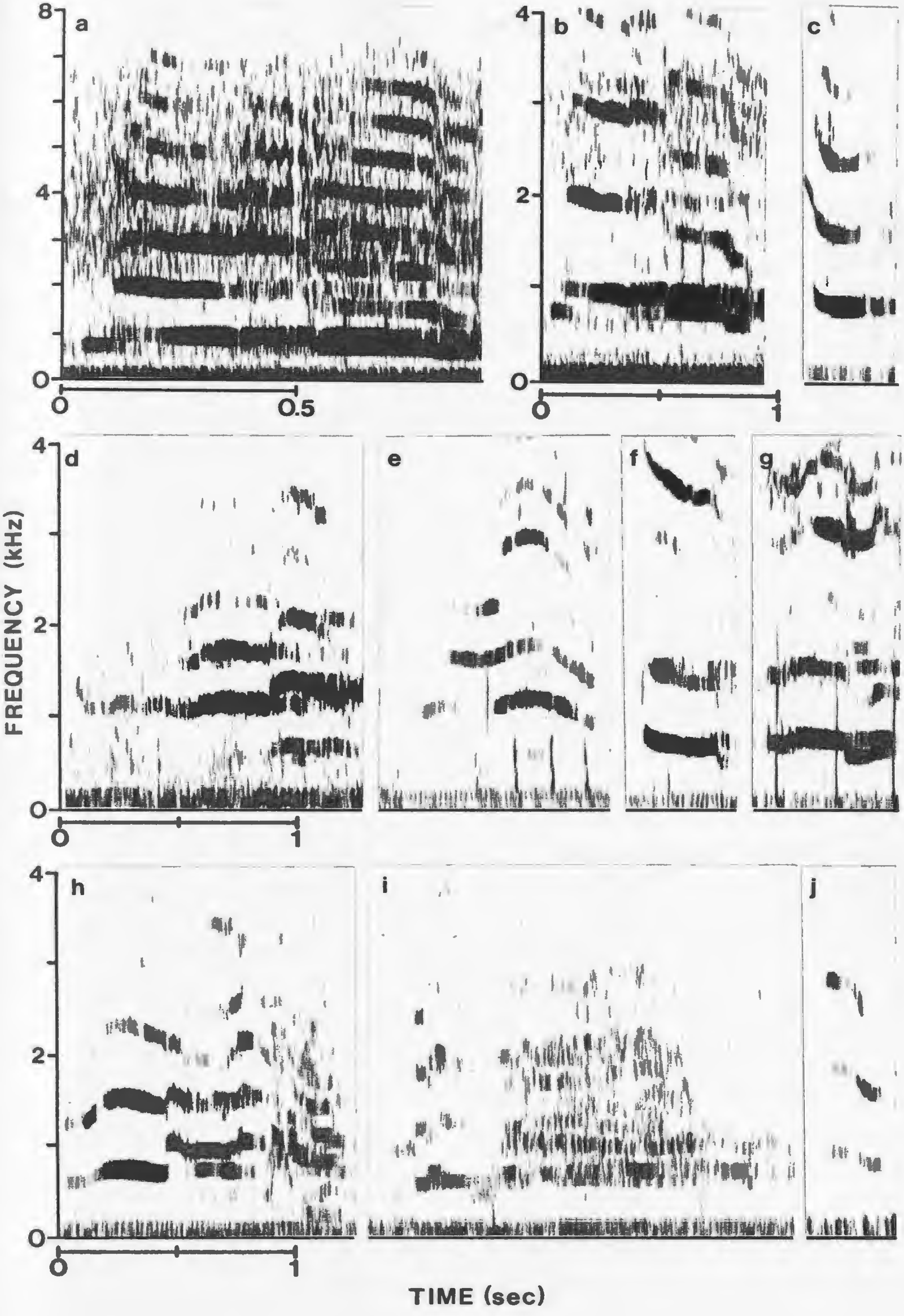
or if the sounds were pulsive for short periods. Mean duration was 1.85 sec (Table 9). Minimum and maximum frequencies averaged 0.49 and 2.30 kHz, for a mean bandwidth of 1.80 kHz. Peak frequency measurements averaged 0.82, 0.83 and 0.68 kHz.

Class 2e included 4 sounds, and ranked twenty-eighth in size. It was well discriminated by cluster analysis, its four members being isolated from any other sound, although one of them was in a separate cluster. Cluster 12 had one case while cluster 13 contained the three others. It is not clear why one sound was kept apart, although its duration was longer (2.18 sec vs a mean of 1.74 sec, Appendix D).

Class 2f. Sounds of this type were mostly tonal, although pulsive sections were common (Figure 14). Four to over ten harmonics were usually present, which resulted in a very broad bandwidth (6.68 kHz). They sounded like trumpeting and usually had their fundamental between 0.7 and 1.5 kHz for most of their duration (Figure 14). Peak frequency averaged 1.34 kHz at the beginning, 1.01 at the middle, and 1.49 at the end (Table 9). Duration varied from 0.26-1.32 sec, for a mean of 0.85. Minimum and maximum frequencies were 0.49 and 7.17 kHz respectively. Many patterns were found. Some had a frequency downsweep at the beginning, followed by a section of more or less constant peak frequency (Figure 14a, c, f, and j). Other sounds were double-humped (Figure 14h), or had very little frequency modulation (Figure 14i), while others had sections containing fewer harmonics (Figure 14d and e).

This was the twenty-first largest class, with 15 cases. Cluster analysis was of limited use in defining this class, splitting it into 14 clusters. However, most cases were isolated from other classes. Twelve clusters were of type "C": cluster 15 had 2 sounds, both from this

Figure 14. Some spectrograms of class 2f sounds. a and b are the same sound, from cluster 19; c is from cluster 2, d from 22, e from 26, f from 24, g from 17, h from 20, i from 21 and j from 25. Analysis filter and breaks in abscissa are as in Figure 6, p. 67.


a
b
c
d
e
f
g
h
i
j
8
4
0
0
0.5
4
2
0
0
1
4
2
0
0
1
4
2
0
0
1
FREQUENCY (kHz)
TIME (sec)

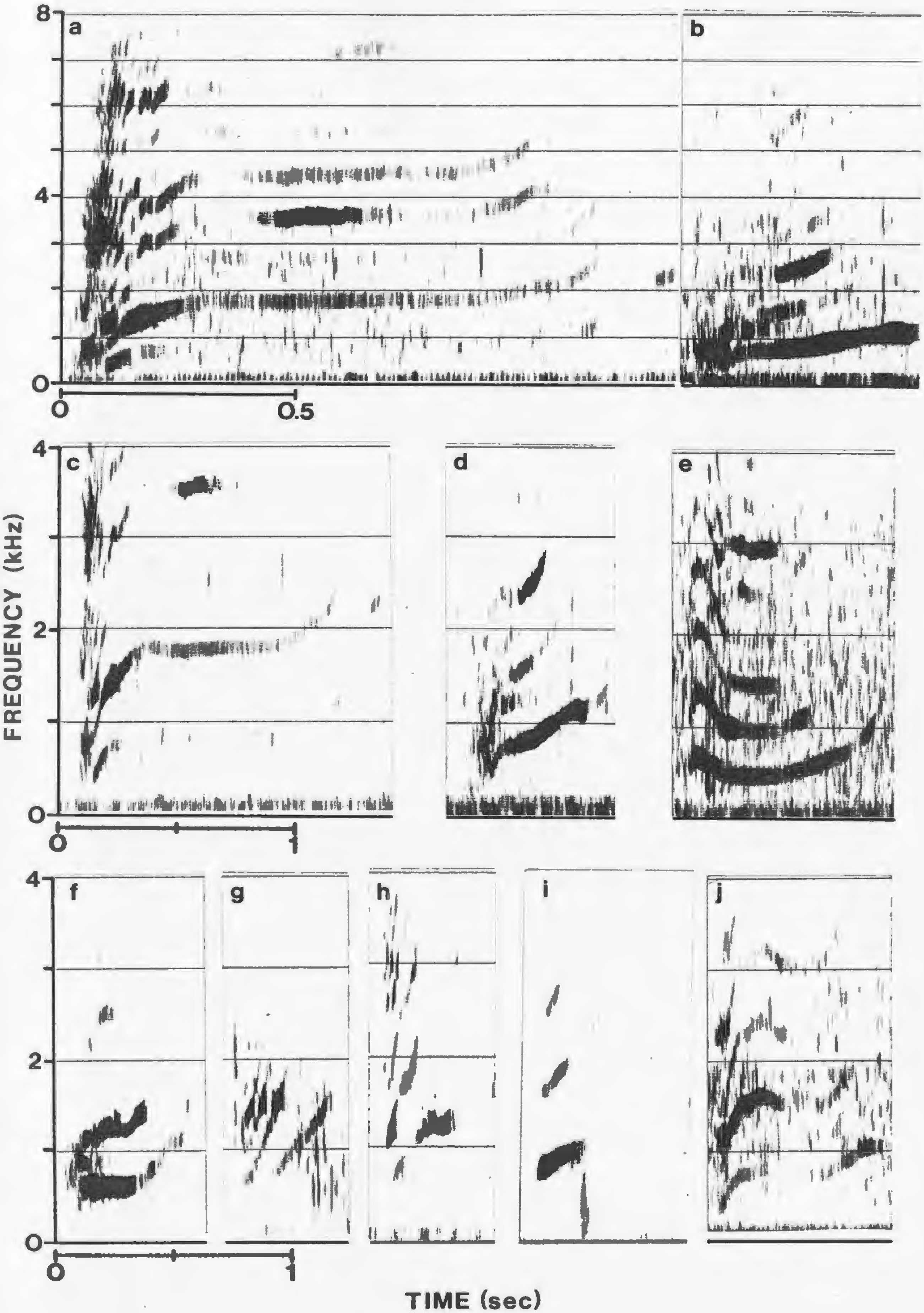
class, while clusters 16-26 had only one case each. Clusters 2 and 14 had one class 2f sound each, but contained mostly sounds of other classes. Variability in duration and, as mentioned earlier, the fact that these sounds were composed of many narrow frequency bands, were probably responsible for the incapacity of cluster analysis to put these sounds together.

Class 2g. Class 2g sounds were tonal with 2-13 harmonics, and consisted primarily of a sharp frequency upsweep. In some cases, this upsweep was followed by a downsweep and then another upsweep, with a lower rate of frequency change (Figure 15). Mean duration was 0.63 sec (Table 9), and the bandwidth was broad (6.26 kHz, with a minimum frequency of 0.45 and a maximum frequency of 6.71 kHz). Peak frequency was 1.39 kHz at the beginning, 1.66 at the middle, and 2.32 at the end.

With 12 cases, it was the twenty-second largest class in the data set. Again, this class was broken up in many clusters. Six clusters contained exclusively sounds of this class. One (27) was of type "B", with three sounds (25%). Clusters 28 and 29 had two sounds each, and 29-31 one sound each. The last two cases were found in cluster 41 and 53, with many sounds of other classes. Variation in duration and the presence of narrow frequency bands were thought to be the reason for the splitting of this class in so many clusters.

Class 2h. These sounds were tonal, but amplitude modulation was sometimes detectable. They consisted of frequency upsweeps (Figure 16), as can be seen in the measurements of dominant frequency: 1.00 kHz at the beginning, 1.23 at the middle and 1.73 at the end (Table 9). They had less energy in low frequencies than sounds of the previous class, and the mean minimum frequency was 0.71 kHz. Few (0-3) harmonics were

Figure 15. Some spectrograms of class 2g sounds. a and c are the same sound, from cluster 28; b and d are the same sound, from cluster 30; e is from cluster 29, f from 30, g-h from 27, i from 41 and j from cluster 31. Analysis filter and breaks in abscissa are as in Figure 6, p. 67.



a
b
c
d
e
f
g
h
i
j
8
4
2
0
0.5
1
FREQUENCY (kHz)
TIME (sec)

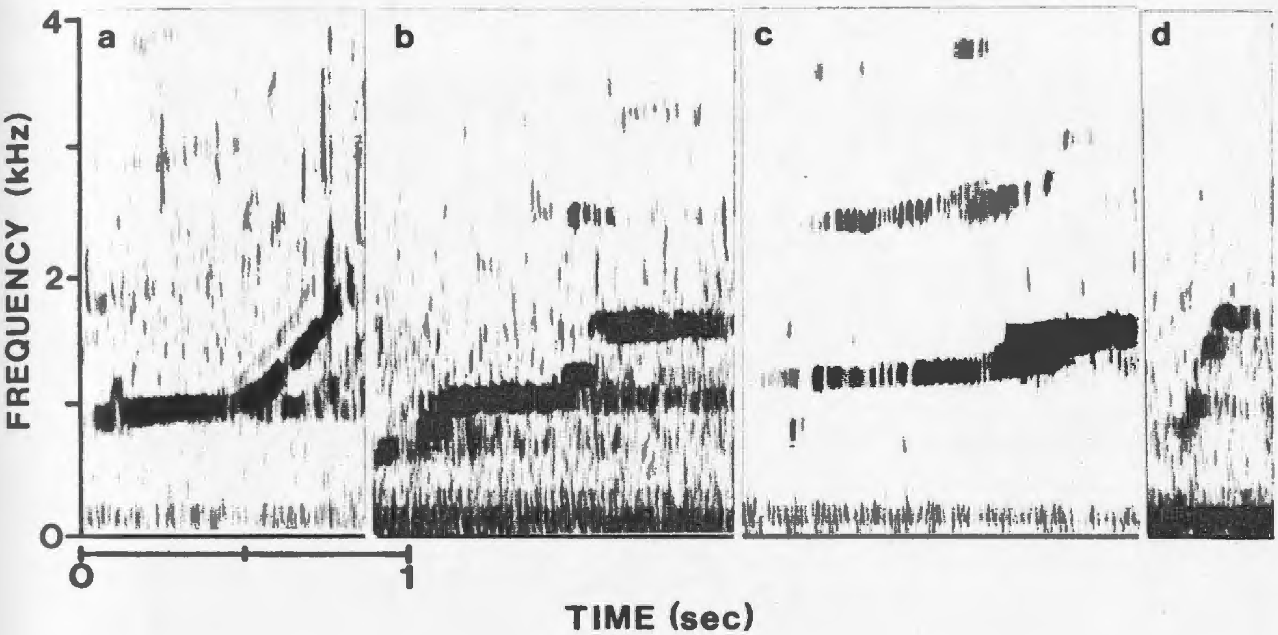


Figure 16. Spectrograms of class 2h sounds. a is from cluster 33, b from 34, c from 35 and d from 41. Analysis filter and breaks in abscissa are as in Figure 6 p. 67.

present, which lowered the mean maximum frequency to 3.07 kHz, for a bandwidth of 2.36 kHz. Duration was very variable, but averaged 0.82 sec.

Class 2h had four elements and ranked twenty-eight overall in size. Three of them were in single-element clusters (clusters 14-16) while the last one was found in cluster 41. This was no surprise, since there was quite a bit of variation in duration, rate of frequency change and shape. In fact the decision of fusing these four sounds in class 2h was difficult. But since they shared the acoustic properties listed above, the author decided to fuse them to keep the size of the repertoire within reasonable limits for further testing.

Class 2i. These sounds were very variable. They seemed to be tonal: the fundamental had a frequency corresponding to the spacing between harmonics. However, the fundamental was the frequency of maximum intensity in only one case. Harmonics were numerous (2-16), which is reminiscent of a pulsive structure, at least for the case with the highest number of harmonics (Figure 17). These sounds were long (mean of 0.6 sec, Table 9) and characterized by their decreasing frequency. However, this was masked from the measurements of peak frequency (2.58, 2.62 and 2.13 kHz at the three sampling points) by the fact that maximum intensity often shifted to higher harmonics toward the end of the sounds. Minimum and maximum frequencies averaged 0.8 and 5.45 kHz respectively, for a mean bandwidth of 4.65 kHz.

With four cases, class 2i ranked twenty-eigth in the repertoire. It was mainly characterized by three type "B" clusters: clusters 113 and 115 had only one case each, while one of the two cases in cluster 114 belonged to class 2i. Duration was very different in these three clus-

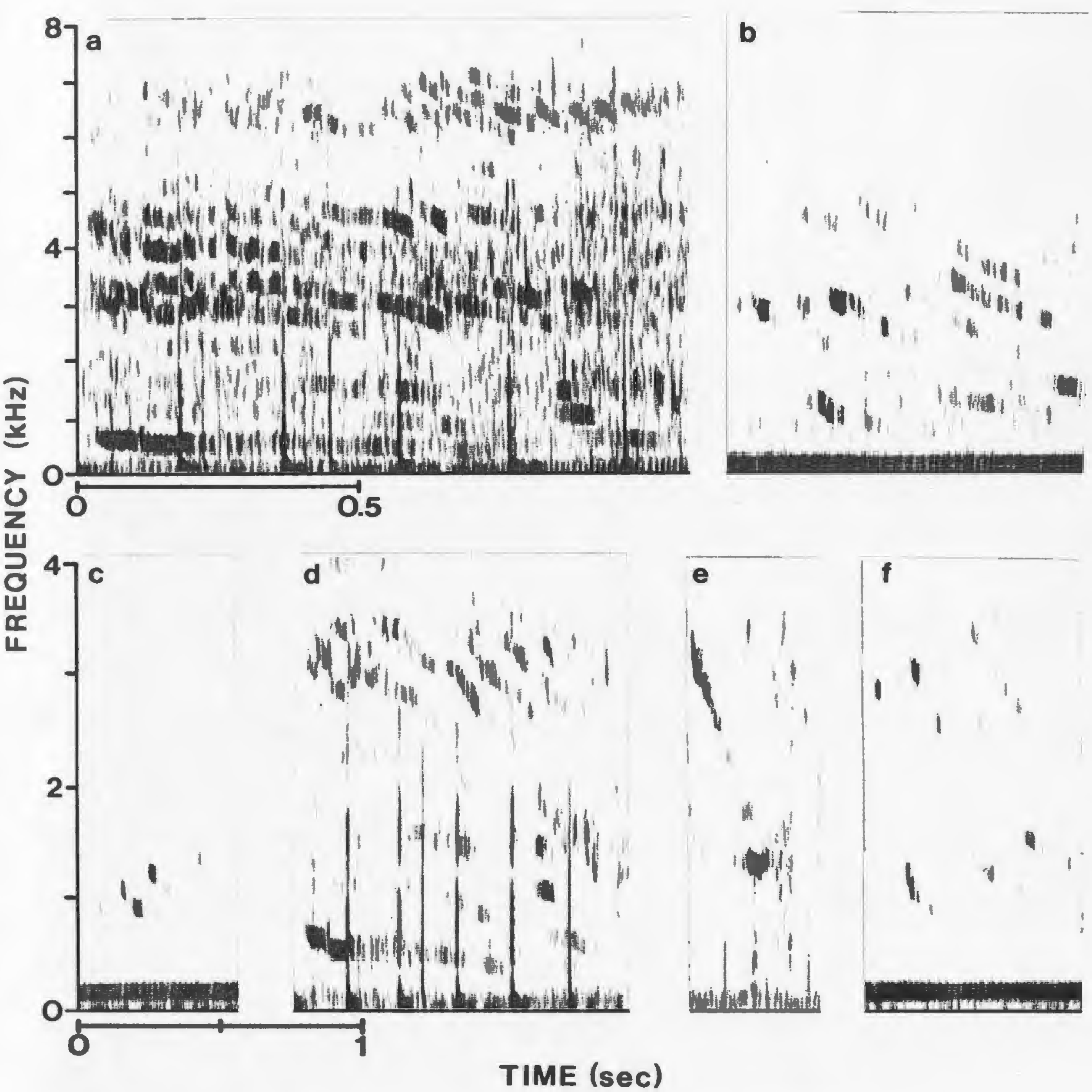


Figure 17. Some spectrograms of class 2i sounds. a and d, and b and f are the same sound. a and d are from cluster 113; b and f are from 115; c is from 48; e is from 114. The clicks present in a and d (0-4 kHz) are from odontocetes. Analysis filter and breaks in abscissa are as in Figure 6, p. 67.

ters: 0.37 sec in cluster 114, 0.67 sec in cluster 115 and 1.08 sec in cluster 113 (Appendix D). Cluster 113 also had more energy in low frequencies, which was indicated by its minimum frequency (0.33 kHz, vs 0.83 and 0.85 kHz in clusters 114 and 115 respectively). The last case came from cluster 48, which also contained seven cases from class 5b, which will be described later. It was the shortest case of the class (mean duration was 0.12 sec in this cluster, Appendix D), had the narrowest bandwidth (mean bandwidth of 1.9 kHz) and little energy above 2 kHz (mean maximum frequency of 2.48 kHz).

GROUP 3.

These sounds were tonal, broadband, but very short (Table 9). Frequency modulation and a few harmonics were generally present. This group was made of five classes.

Class 3a. This class had a single case. It was composed of two subunits, each one being a tonal frequency upsweep (Figure 18a). Two harmonics were present for each subunit. This vocalization sounded unitary to the human ear when played back at normal speed. Echo was ruled out by looking at other sounds produced shortly before and after this one, and by listening to the sound at half speed. Duration was 0.13 sec and bandwidth 3.46 kHz (Table 10). Minimum and maximum frequencies were 0.43 and 3.89 kHz respectively. Peak frequency measurements were 0.58, 0.79 and 0.70 kHz at the three sampling points. This class was not well recognized by cluster analysis: it was found in cluster 39, with three cases of class 3b sounds. It was put apart by the author because of its structure.

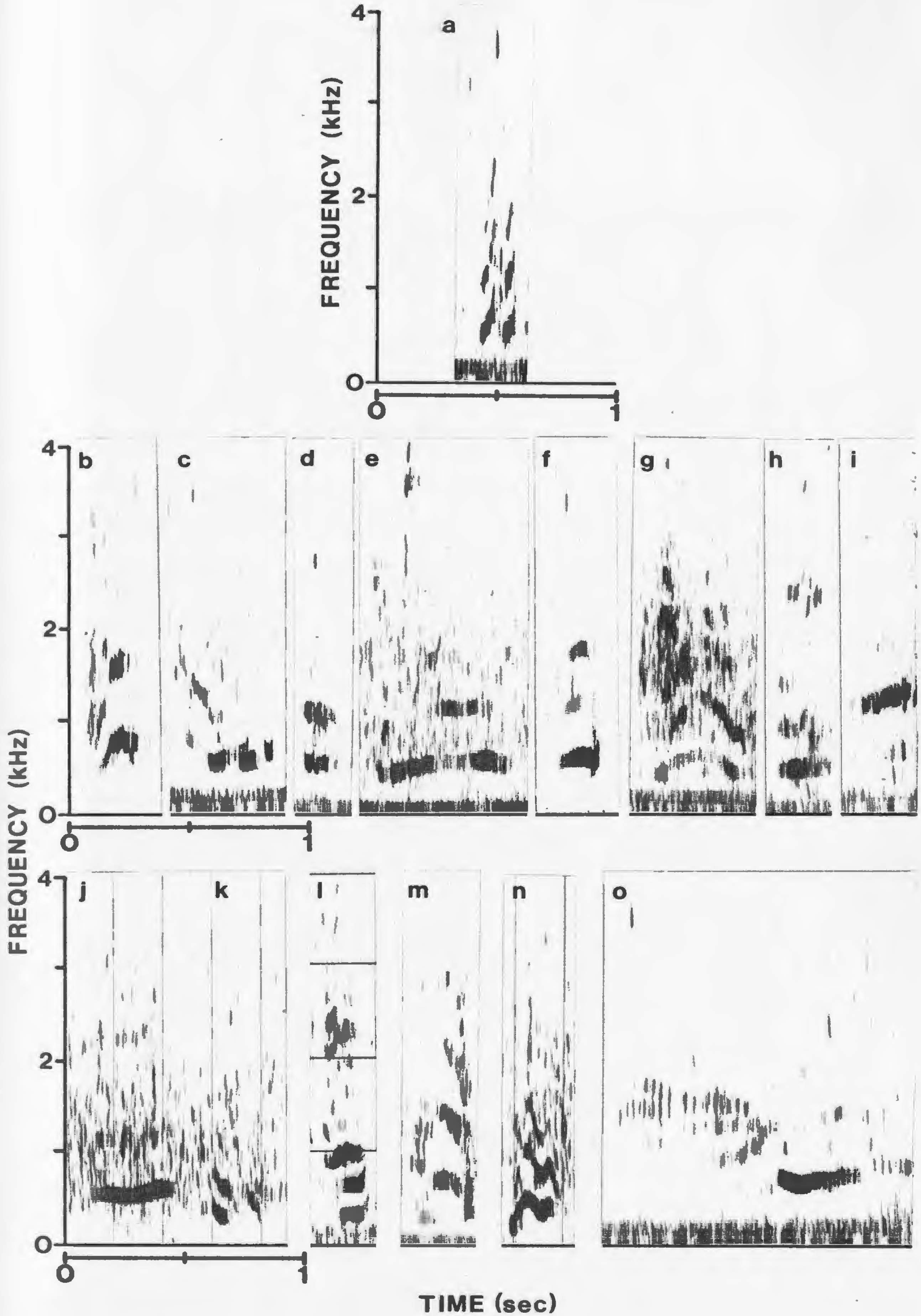
Table 10. Characteristics and clustering of the five classes of Group 3.

For each class, the number of cases (n), mean dominant frequency at three points (start, middle, and end of sound), minimum and maximum frequencies, and duration are given, with the standard deviation in brackets. Structure of the sounds and the number of clusters of each type are also shown. The highest proportion (%) of the class found in a single cluster is in brackets, below the appropriate cluster type.

CLASS (n)	DOMINANT FREQ (kHz)			MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)	STRUCTURE *	CLUSTER TYPE **					
	START	MIDDLE	END					A	B	C	D	E	F
3a	0.58	0.79	0.70	0.43	3.89	0.13	TH				1		
(1)	-	-	-	-	-	-					(100)		
3b	1.07	0.95	0.67	0.41	3.03	0.32	TH(SF)			5			5
(19)	(0.53)	(0.41)	(0.25)	(0.22)	(1.73)	(0.33)				(16)			
3c	3.68	4.17	5.05	2.58	6.62	0.05	TH	1					2
(139)	(1.34)	(1.06)	(1.33)	(1.36)	(1.23)	(0.03)		(96)					
3d	0.65	0.88	5.57	0.16	7.09	0.16	STH	1		2			2
(29)	(0.47)	(1.33)	(1.25)	(0.06)	(0.98)	(0.04)		(76)					
3e	0.69	1.25	1.28	0.12	3.86	0.06	NT					1	
(1)	-	-	-	-	-	-						(100)	

* Structure types are as in Table 6, p. 64.
** Cluster types are described in Table 5, p. 62.

Figure 18. Spectrogram of class 3a sound (a), and some spectrograms of 3b sounds (b-o). a was from cluster 39; b-c from 2; d from 36; e and g from 37; f and j from 39; h from 57; i from 41; k-l from 40; m from 51; n from 58; o from 38. Analysis filter and breaks in abscissa are as in Figure 6, p. 67.


a
b
c
d
e
f
g
h
i
j
k
l
m
n
o
FREQUENCY (kHz)
FREQUENCY (kHz)
4
2
0
0
1
TIME (sec)

Class 3b. Dominant frequency was highly variable in these sounds, as can be seen in Figure 18b-o. However, they all shared the following characteristics: short duration (mean of 0.32 sec, Table 10), often tonal but sometimes pulsive, usually with one or two harmonics. Few exceptions had up to eight harmonics (and were pulsive), or no harmonics. The peak frequency was sometimes almost constant, but the most common form was an inverted "U" shape, the frequency going up by a few hundreds Hz and then back around its original value. However some up-down-up forms were also found. One case even started with a faint but long pulsive portion (Figure 18o). On the average, the 3 peak frequency measurements were 1.07, 0.95 and 0.67 kHz, and the mean bandwidth was 2.62 kHz. Minimum and maximum frequencies averaged 0.41 and 3.03 kHz respectively.

Nineteen sounds were identified in this class, the nineteenth largest in the repertoire. Class 3b was split in many small clusters, most of which being of type "C" and containing almost exclusively this type of sounds. The highest number (three or 16%) was found in cluster 36, which contained no other sound. Clusters 37 and 38 had two and one cases respectively. Clusters 39 and 40 had three class 3b sounds each, but also contained one other sound. The last two were in cluster 41, where they accounted for only 1% of the cluster. Differences in duration and frequencies appeared to be the reason for this splitting. For example, the sound with a long pulsive portion, just described, was much longer than the others (1.6 sec, Appendix D) and was clustered alone in cluster 38. Duration was 0.50 sec in cluster 37, and 0.23, 0.21 and 0.20 sec in clusters 39, 40 and 36 respectively. Among the three clusters with similar duration, one (36) had a much broader bandwidth (4.22 kHz). It is not clear why the last two were differentiated.

Class 3c. Sounds of this class were very short (mean duration was only 0.05 sec, Table 10) frequency modulated pure tones with one or more harmonics (Figure 19). Some harmonics were frequently above the upper limit of analysis (8 kHz). Most cases were frequency upsweeps with a fairly constant slope, although plateaus were common. More rarely, one to three inflection points were present, as in down-up (e.g., Figure 19n-q) and down-up-down-up sounds (Figure 19m,r). There were a few instances of downsweeps, i.e., frequency at the end dropped below the initial frequency (Figure 19i). These sounds had little energy below 3 kHz, and minimum frequency averaged 2.58 kHz. Because harmonics frequently rose out of range, maximum frequency averaged 6.62 kHz, for a mean bandwidth of 4.04 kHz. The frequency upsweep was well revealed in the measurements of dominant frequency: 3.68 kHz at the beginning, 4.17 at the middle, and 5.05 at the end. On one occasion, the fundamental was above 8 kHz.

There were 139 class 3c sounds among the 1255 sounds of the sample, and it was the second largest class. It was well revealed by cluster analysis, cluster 41 containing 134 cases, or 96.4% of the class and 93.1% of the cluster. Three more cases were found in cluster 45, which was characterized by a constant peak frequency (Appendix D), and the last two in cluster 103.

Class 3d. These sounds had two sections of very different properties (Figure 20). The first section was composed of one or more low frequency clicks, being very similar to some class 4a or 5b sounds, which will be described later. The last portion was identical to class

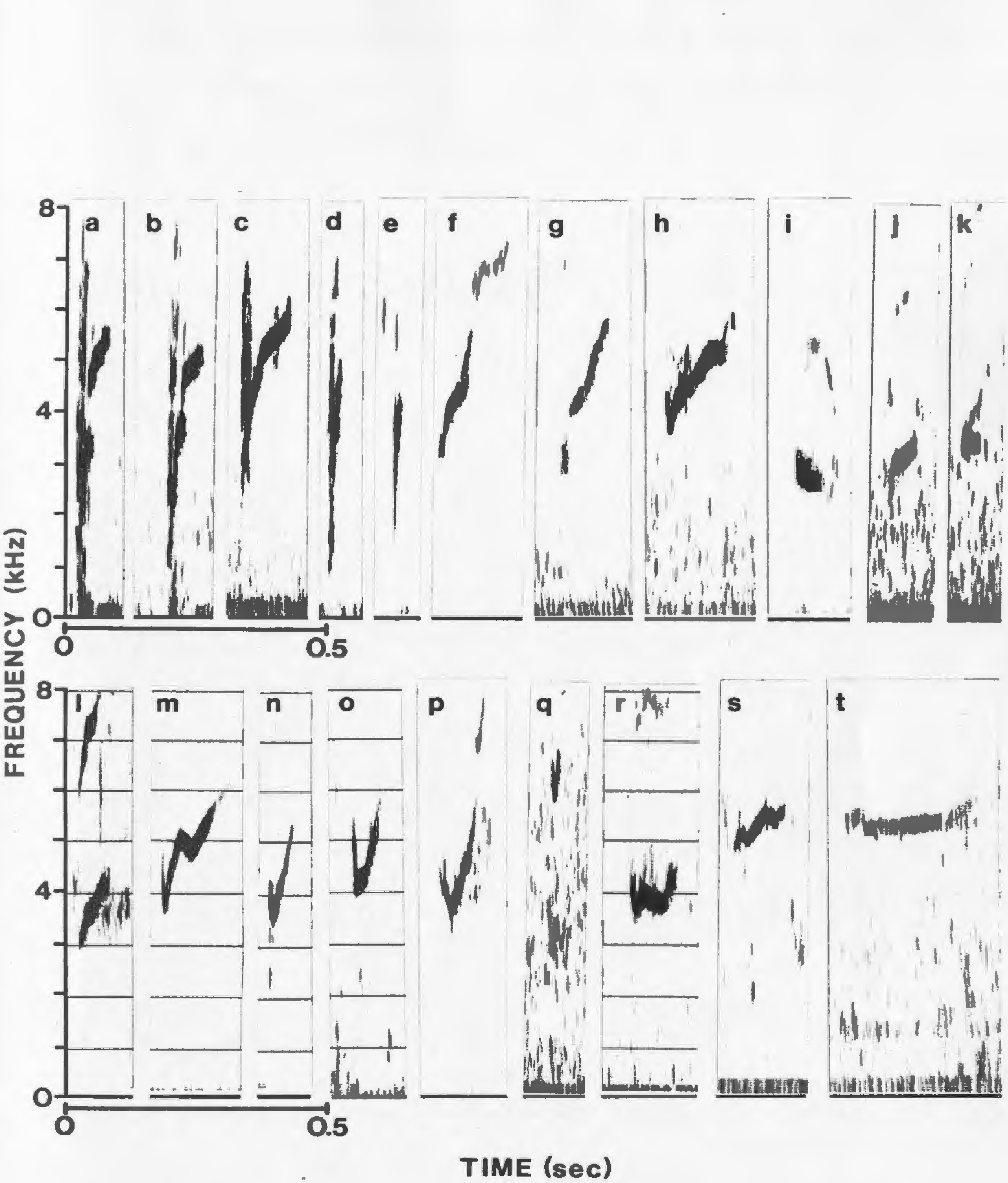


Figure 19. Some spectrograms of class 3c sounds. e is from cluster 103; all other cases are from cluster 41. Analysis filter and breaks in the abscissa are as in Figure 6 p. 67.

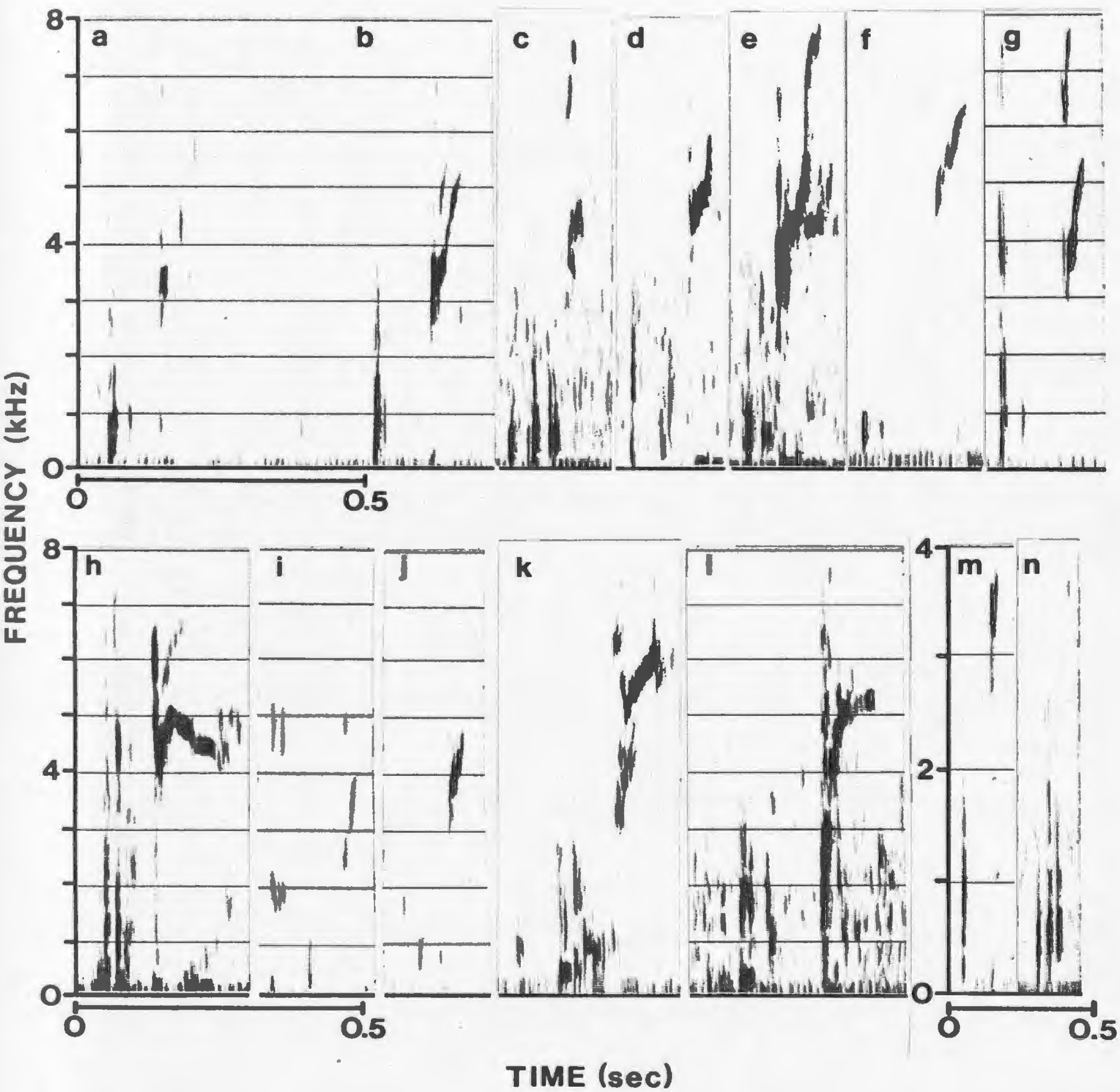


Figure 20. Some spectrograms of class 3d sounds. a-h are from cluster 42, as well as m and n, which are the same sound as b and c, respectively; i is from 43; j is from 44; k is from 50; l is from 51. Analysis filter and breaks in the abscissa are as in Figure 6 p. 67.

3c sounds. It was debatable whether one or two sounds were involved here, but in accordance with the definition of sound unit used in this study, it was decided to make a class of these sounds. An argument in favor of this decision was the consistency of the timing between the two parts of the sounds (Figure 20).

Mean duration and bandwidth were 0.16 sec and 6.93 kHz, respectively (Table 10). Average peak frequency was 0.65 kHz at the beginning (in the pulsive section), 0.88 kHz at the middle (end of pulsive section and beginning of tonal section), and rose to 5.57 kHz at the end of the tonal upsweep. As for class 3c sounds, harmonics were common in the second section, and often above the limit of present analysis (8 kHz).

With 29 cases, class 3d ranked twelfth overall in size. It was easily revealed by cluster analysis, cluster 42 containing 76% of its members and being devoted at 96% to this class. Cluster 43, with a single member, was considered an extreme case: it started with clicks of broad frequencies, but with little energy below 1.5 kHz (Figure 20i). The rest of its properties fell within the normal range for the class. Cluster 44 had two of its four members in class 3d. It is not clear why they were kept apart from the other class members, but they were among the shortest in this class, mean duration being 0.11 sec in cluster 44, versus 0.15 and 0.14 in clusters 42 and 43 respectively (Appendix D). The bandwidth was also reduced to 4.07 kHz, against 6.99 in cluster 42 and 7.20 in cluster 43, mainly because of the absence of harmonics. These two sounds might have come from more distant whales. Three more cases were found in cluster 51, and another in cluster 50, with many sounds of other types.

Class 3e. This type could be described as a class 3c sound of unusually low frequency (Figure 21). Duration was very short (0.06 sec, Table 10) and bandwidth broad (3.74 kHz), but there was little energy above 1.5 kHz. The measurements of peak frequency were 0.69, 1.25 and 1.28 kHz. Minimum and maximum frequencies were 0.12 and 3.86 kHz respectively. Only one such sound was found in the data set, and it was not recognized by cluster analysis: it was placed with the many class 3c sounds in cluster 41.

GROUP 4.

These sounds were very short. Noise was generally prominent, which resulted in broad bandwidths. They had a click-like structure. Two classes were represented in group 4 (Table 11).

Class 4a. This class comprised simple click-like sounds, of variable but often broad bandwidth (mean of 2.44 kHz). Energy was usually very high in the low frequencies, with a mean minimum frequency of 0.23 kHz, and mean peak frequencies of 0.79, 0.60 and 0.58 kHz at the three sampling points (Table 11). Maximum frequency averaged 2.67 kHz. Even if the energy was pretty well distributed on the whole bandwidth, bands of higher amplitude were often present (Figure 22). Duration averaged 0.04 sec. One or two other clicks, usually of much lower intensity, were sometimes found before or after the main click. They were barely audible to a human listener. Class 4a corresponds to the "broadband clicks" of Winn et al. (1979).

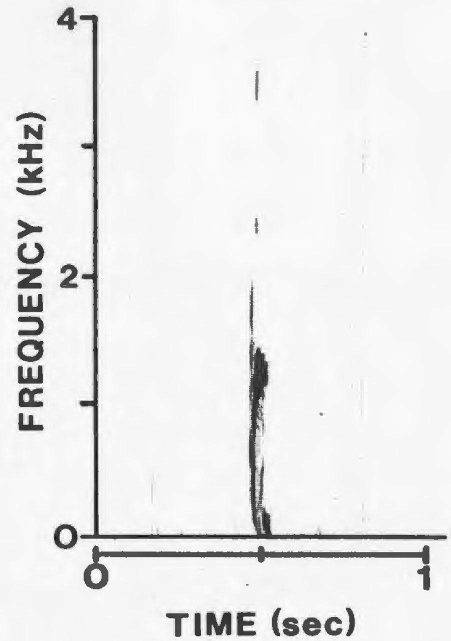


Figure 21. Spectrogram of class 3e sound. Analysis filter is as in Figure 6, p. 67.

Table 11. Characteristics and clustering of the two classes of Group 4.

For each class, the number of cases (n), mean dominant frequency at three points (start, middle, and end of sound), minimum and maximum frequencies, and duration are given, with the standard deviation in brackets. Structure of the sounds and the number of clusters of each type are also shown. The highest proportion (%) of the class found in a single cluster is in brackets, below the appropriate cluster type.

CLASS (n)	DOMINANT FREQ (kHz)			MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)	STRUCTURE *	CLUSTER TYPE **					
	START	MIDDLE	END					A	B	C	D	E	F
4a (64)	0.79 (0.72)	0.60 (0.49)	0.58 (0.55)	0.23 (0.29)	2.67 (1.76)	0.04 (0.04)	NT(S)		1 (47)	1			6
4b (8)	1.01 (0.83)	0.60 (0.65)	0.91 (1.48)	0.14 (0.02)	5.78 (2.10)	0.07 (0.02)	NT					1 (88)	1

* Structure types are as in Table 6, p. 64.
** Cluster types are described in Table 5, p. 62.

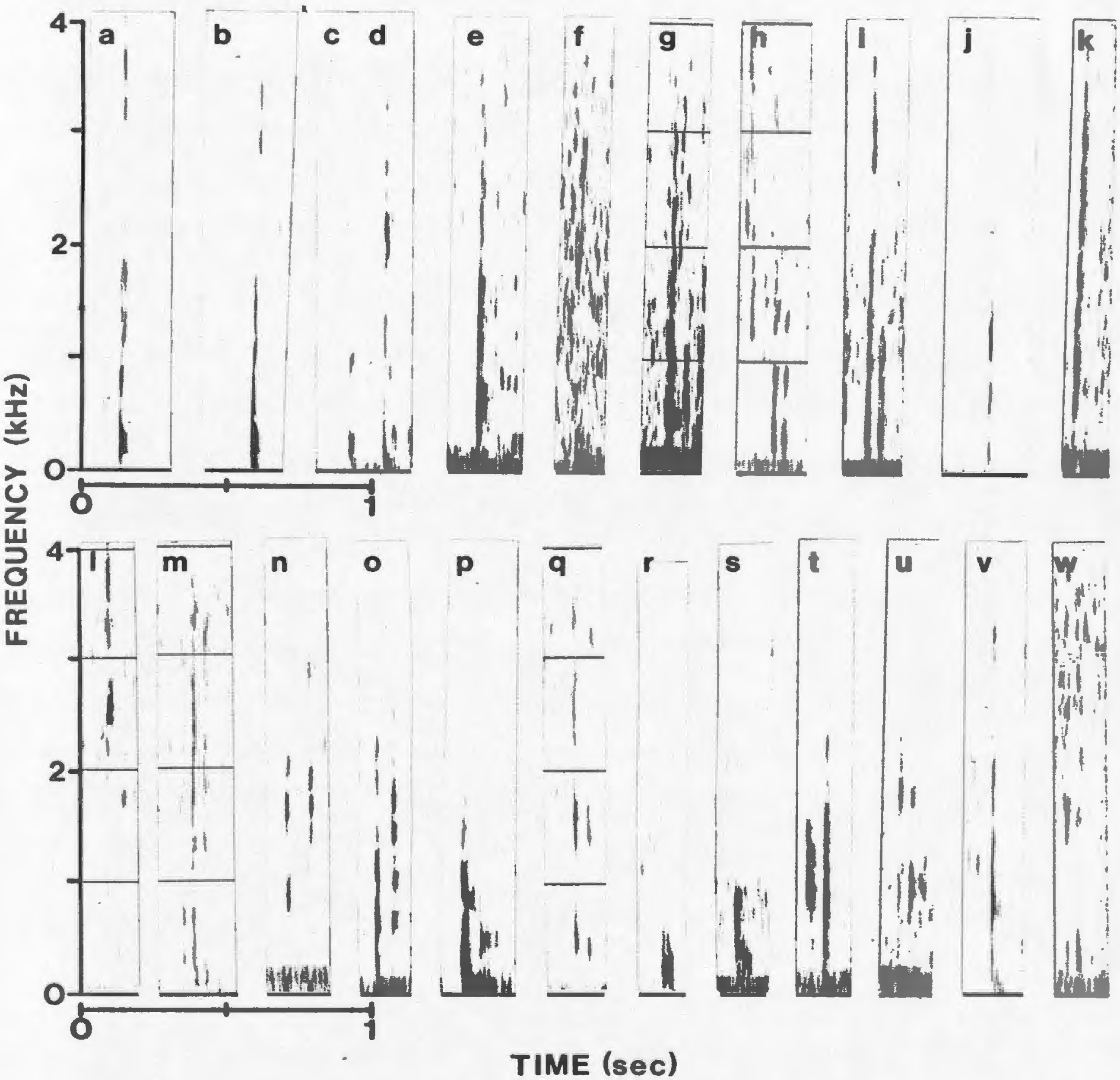


Figure 22. Some spectrograms of class 4a sounds. a-i are from cluster 46; j-l from 45; m-o from 50; p from 51; q-s from 55; t-w from 56. Analysis filter and breaks in the abscissa are as in Figure 6, p. 67.

Class 4a had 64 sounds and was the sixth largest in the sample. It had one type "B" cluster: 30 cases or 47% came from cluster 46, and 77% of the sounds of this cluster belonged to this class. Four other cases were found in cluster 45 (type C). For them, there was no low energy (mean minimum frequency of 1.32 kHz, versus 0.18 in cluster 46, Appendix D). This cluster also had three sounds from class 3c. This was not surprising: once digitized, class 3c and 4a sounds were very much alike, except that the later usually scored better in low frequencies. A few other cases were found in clusters 47, 50-51, and 55-57. Most of them were preceded or followed by additional clicks and consequently had a longer duration (mean duration was 0.08-0.23 sec in these clusters, vs 0.04 in cluster 46, Appendix D).

Class 4b. This class was one of the three that correlated with whales' behavior. They were recorded while a whale was lobtailing (slapping its tail on the surface of the sea), flippering (slapping of one or both flippers on the surface) or breaching (whale leaping out of the water), and were identified as impact noises. Such sounds have been described as broadband pulses by Thompson et al. (1977). These sounds were difficult to digitize, being usually characterized by strong echoes, hard to separate from the sound itself. They were short (mean of 0.07 sec, Table 11) broadband sounds (mean bandwidth of 5.64 kHz) and had their strongest amplitude in low frequencies (peak frequency measurements of 1.01, 0.60 and 0.91 kHz) (Figure 23). Minimum and maximum frequencies were 0.14 and 5.78 kHz.

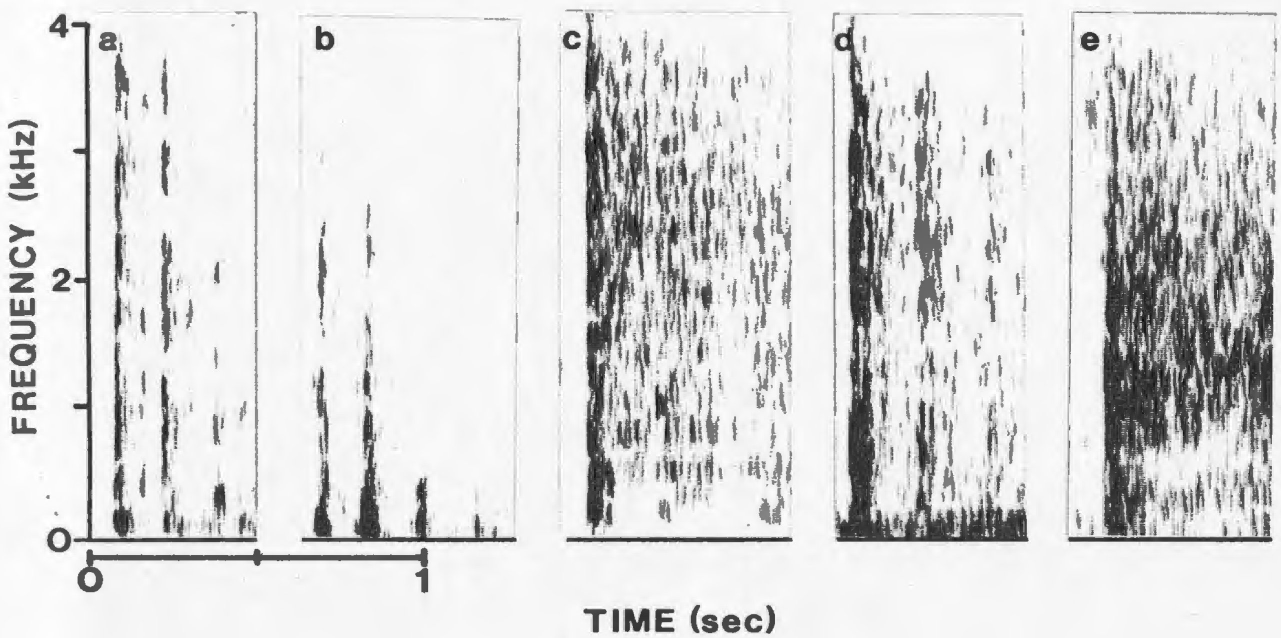


Figure 23. Some spectrograms of class 4b sounds. a-d are from cluster 46; e is from cluster 42. Echoes are prominent on these spectrograms. Analysis filter and breaks in the abscissa are as in Figure 6, p. 67.

Class 4b had eight cases, and ranked twenty-third in size. However, they occurred more often than their poor representation in the sample might suggest: often too much noise and echo was masking them, and few were digitized. Echo seems to be an important factor for aural recognition of these sounds, but was not digitized. For this reason, these sounds were very similar to class 4a sounds once digitized. Not surprisingly, seven of them (88%) were clustered in cluster 46, with most of 4a sounds. The other case, longer, was in cluster 42, with class 3d sounds. Cluster analysis did not recognize this class.

GROUP 5.

Sounds in this group were pulsive, with a repetition rate usually slow enough to distinguish their individual subunits (although one class had a very variable repetition rate). Peak energy was generally between 0.5 and 1.5 kHz, and often (but not always) increased toward the end of the sounds. Duration was short, averaging 0.09-0.18 sec for four of the five classes in this group (Table 12).

Class 5a. Here, sounds were made of 3-10 simple click-like structures of more or less equal intensity (Figure 24). The repetition rate was always slow enough to permit a good separation of each click with the analysis filter used (150 Hz). Mean duration was 0.13 sec (Table 12); minimum and maximum frequencies averaged 0.18 and 1.49 kHz respectively, for a mean bandwidth 1.31 kHz. It can be seen in the measurements of peak frequency that most of the energy was in low frequencies: 0.51, 0.44 and 0.45 kHz. With 21 cases, it was the seventeenth largest class in the sample. It was not recognized in cluster analysis. Ten

Table 12. Characteristics and clustering of the five classes in Group 5.

For each class, the number of cases (n), mean dominant frequency at three points (start, middle, and end of sound), minimum and maximum frequencies, and duration are given, with the standard deviation in brackets. Structure of the sounds and the number of clusters of each type are also shown. The highest proportion (%) of the class found in a single cluster is in brackets, below the appropriate cluster type.

CLASS (n)	DOMINANT FREQ (kHz) START	MIDDLE	END	MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)	STRUCTURE *	CLUSTER TYPE ** A	B	C	D	E	F
5a (21)	0.51 (0.29)	0.44 (0.25)	0.45 (0.31)	0.18 (0.10)	1.49 (0.77)	0.13 (0.08)	S						6 (48)
5b (134)	1.13 (0.69)	1.01 (0.72)	1.30 (0.71)	0.32 (0.24)	3.92 (2.05)	0.15 (0.08)				8			6 (21)
5c (3)	1.03 (0.52)	0.74 (0.43)	1.73 (0.13)	0.12 (0.01)	5.25 (1.41)	0.18 (0.03)	FN					1 (67)	1
5d (1)	0.51 -	1.50 -	1.29 -	0.13 -	6.08 -	0.10 -	SN					1 (100)	
5e (1)	0.78 -	0.12 -	1.31 -	0.12 -	4.04 -	0.71 -	SN					1 (100)	

* Structure types are as in Table 6, p. 64.
** Cluster types are described in Table 5, p. 62.

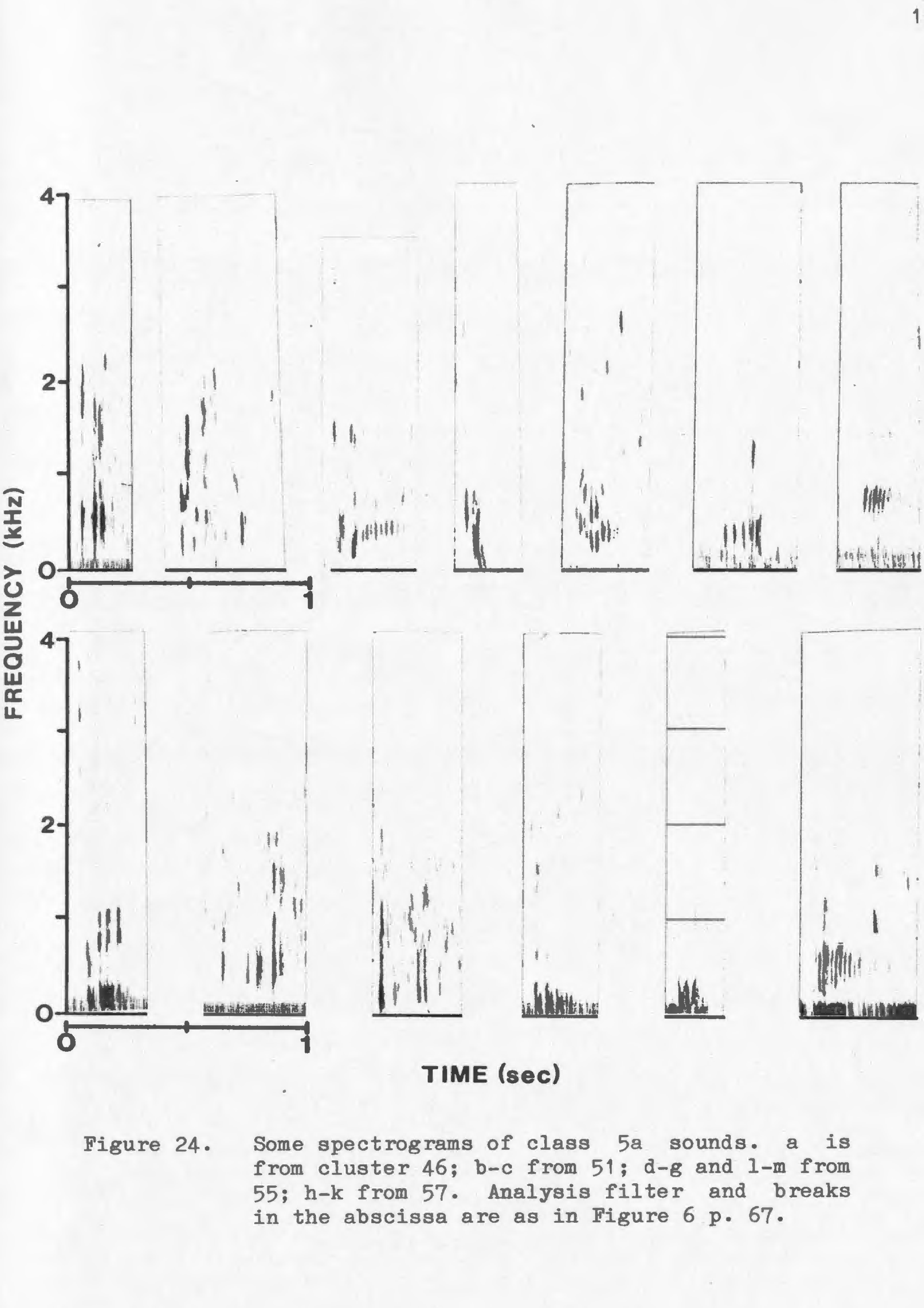


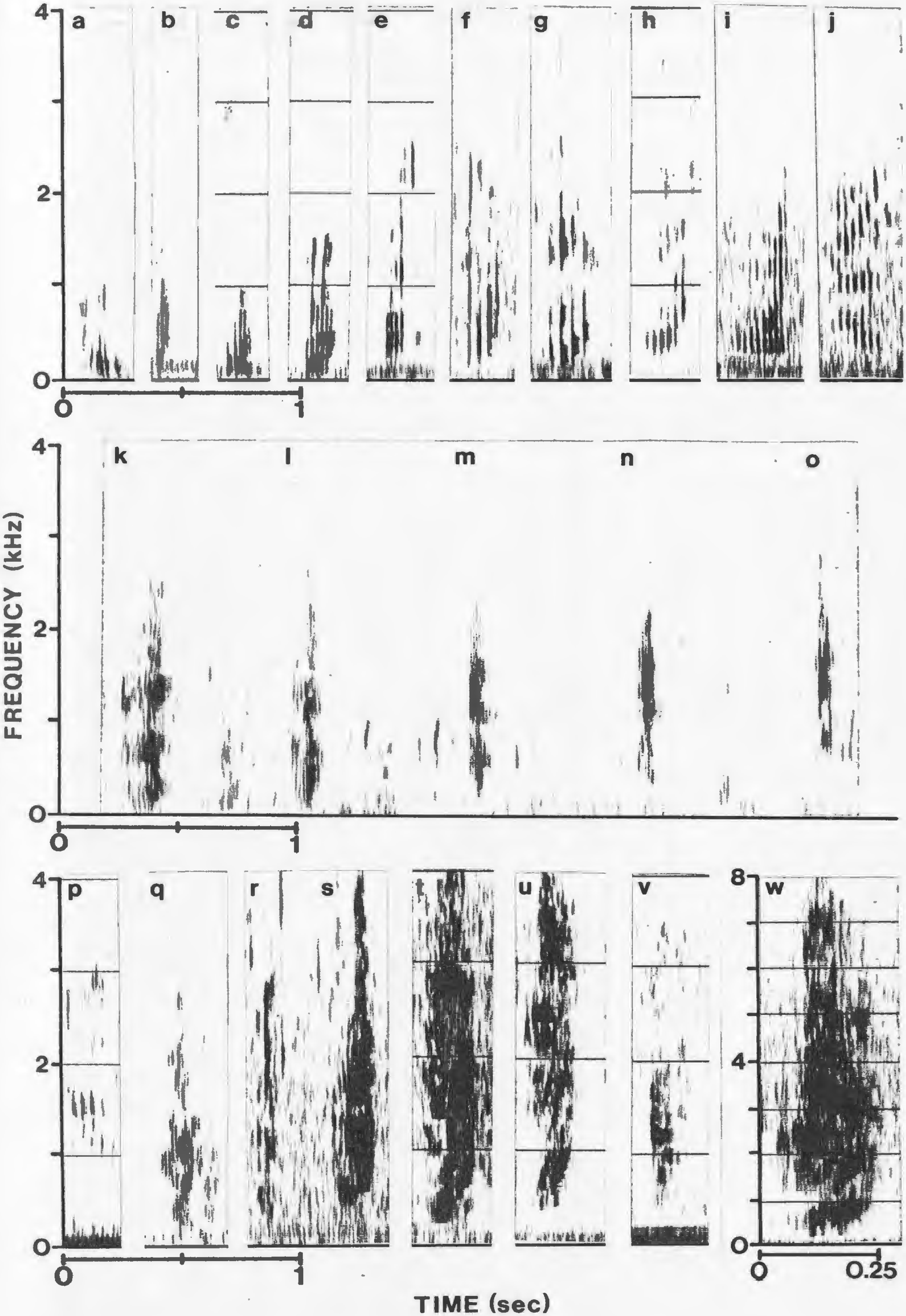
Figure 24. Some spectrograms of class 5a sounds. a is from cluster 46; b-c from 51; d-g and l-m from 55; h-k from 57. Analysis filter and breaks in the abscissa are as in Figure 6 p. 67.

cases (48%) were in cluster 55, where they accounted for 36% of the cases. One to five cases were found in clusters 46, 51, 56-57 and 109. They were found in the same clusters as classes 4a and 5b. A combination of many factors was probably responsible for this: there was quite a bit of variability in dominant frequencies, and sometimes no region of higher energy was visible, both resulting in variable measurements of peak frequency; duration and bandwidth, as well as the interaction of the two, also affected clustering. Cluster 46 had short sounds with a broad bandwidth (3.04 kHz). Those found in clusters 55 and 56 were of about the average duration for the class, with a broad bandwidth in cluster 56 and a much narrower bandwidth in 55. Clusters 51, 57 and 109 were longer than average and had broad bandwidths.

<u>Class 5b.</u> Sounds of this class were similar to those of class 5a in being pulsive and of relatively short duration (0.15 sec, Table 12). However they were of a broader bandwidth (3.60 kHz): minimum frequency was higher (0.32 kHz), but more importantly, mean maximum frequency was 3.92 kHz. Mean peak frequency was 1.13 kHz at the beginning, 1.01 at the middle and 1.30 at the end, which shows that there was less energy in low frequencies than for the previous class. Even if it is not very apparent from these measurements, peak frequency often rose toward the end of the sounds, chiefly for the sounds of fastest repetition rate. Repetition rate was very variable: the individual clicks of some sounds were readily distinguishable, while a complex harmonic structure took place in other sounds (Figure 25). Noise was present in most cases.

There were 134 cases in class 5b, which was the third largest in the repertoire. Cluster analysis did not discriminate well between classes 4a, 5a and 5b. Class 5b was split in many smaller clusters dur-

Figure 25. Some spectrograms of class 5b sounds. u and w are the same sound. a-b, d-e, and g-i are from cluster 57; c-d, f, and j-l from 51; m and r from 56; n-o, s, u and w from 49; p from 47; q and t from 50; v from 48. Analysis filter and breaks in abscissa are as in Figure 6, p. 67.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FREQUENCY (kHz)
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ing cluster analysis. Eight of them were of type "C", thus containing mostly sounds of this type: clusters 44, 47-50, 52-53 and 56. However, only 2-19 cases belonging to class 5b were found in any of them. In fact, the cluster accounting for the highest number of these sounds was of type "F": cluster 57 had 28 cases (21% of the class, and 18% of the cluster). Cluster 51 had the second largest number of cases from this class: 23, or 17%. Again, they accounted for only 33% of the cluster. Other cases were found in clusters 2, 54-55 and 103. Variation in duration and bandwidth were probably responsible for this. Mean duration was shorter than the class average in clusters 44, 47-48, and 55-56; it was about the class average in cluster 53, and longer in clusters 2, 49-50, 52, 54, 57 and 103. Mean minimum frequency was lower than the class average in clusters 54-57; it was about the class average in clusters 44, 50, and 52, while it was higher in clusters 2, 47-49, 53 and 103. Finally, clusters 47-48, 53, 55 and 57 had relatively narrow bandwidths; clusters 2, 44, 50, 54 and 56 had bandwidths near the class average; and clusters 49, 52 and 103 had broad bandwidths (Appendix D). These clusters were fused because of their very similar acoustic properties and of the gradation between clusters.

<u>Class 5c.</u> The spectrograms of these sounds (Figure 26) look much like those of class 5b having a fast repetition rate. However, the aural impression was most peculiar: it was very loud, with a very sudden start, sounding like a bark. Bandwidth was very broad (5.13 kHz), and much noise was present. Most of the energy was below 2 kHz, and not distributed equally. Measurements of peak frequency averaged 1.03, 0.74 and 1.73 kHz at the three sampling points (Table 12). Mean minimum frequency was 0.12 kHz, and mean maximum frequency 5.25 kHz. Duration was

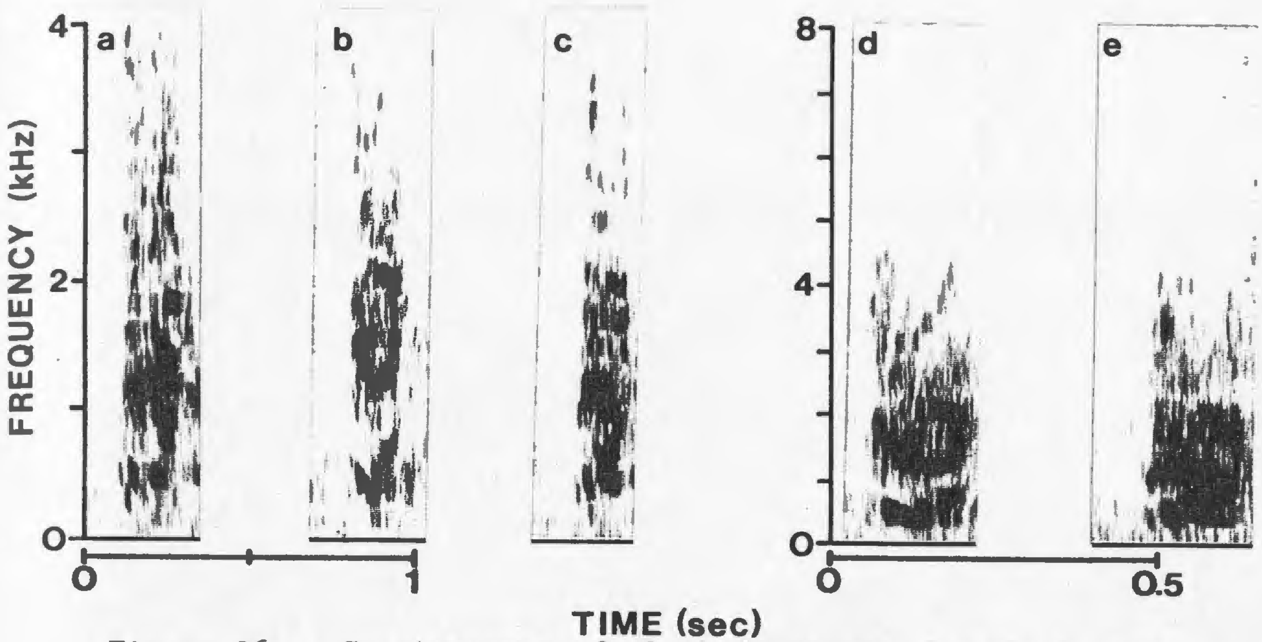


Figure 26. Spectrograms of class 5c sounds. b and d are the same sound, as well as c and e. a is from cluster 50. b-e are from cluster 51. Analysis filter and breaks in abscissa are as in Figure 6 p. 67.

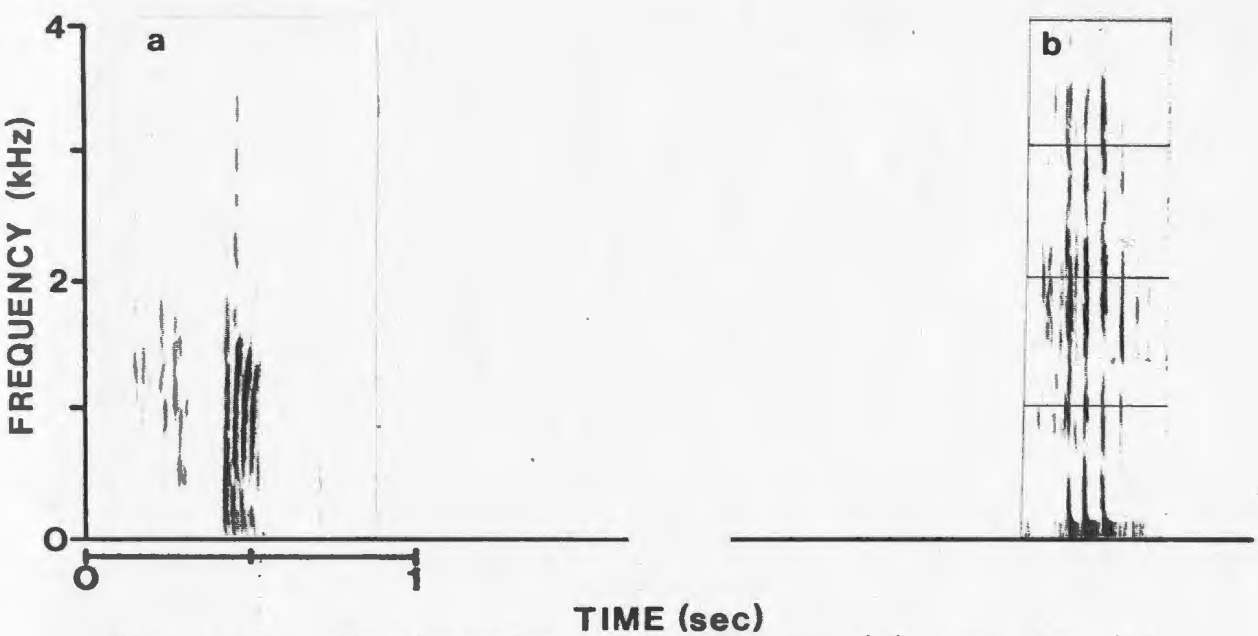


Figure 27. Spectrograms of class 5d (a) and 5e (b) sounds. a is from cluster 50; b is from cluster 51. Analysis filter and breaks in abscissa are as in Figure 6 p. 67.

0.18 sec.

Class 5c had only three members, and ranked thirty-fifth in size. Cluster analysis did not differentiate it from class 5b. Two of its members (67%) were found in cluster 51, accounting for only 3% of this cluster, and the other in cluster 50, also accounting for 3% of the cluster.

Class 5d. There was only one sound in this class. It was pulsive (Figure 27a), and the four individual clicks were well separated. Each click was much like the sound identified as class 3e (Figure 21, p. 102). It sounded very different from any other sound in the sample. Duration was 0.1 sec, minimum frequency 0.13 kHz, and maximum frequency 6.08 kHz, for a bandwidth of 5.95 kHz (Table 12). However, only the second click had energy above 2 kHz. Peak frequency was 0.51 kHz at the beginning, 1.5 at the middle and 1.29 at the end.

This sound was not distinguished from class 5a by cluster analysis, as it was included in cluster 50.

Class 5e. Again, only one case was found in this class. This sound (Figure 27b) consisted of three broadband clicks plus a few fainter and narrower ones. Each click was very similar to some sounds of class 4a. It lasted 0.71 sec, with a frequency range of 3.92 kHz (Table 12). Peak frequency measurements were 0.78, 0.12 and 1.31 kHz. Minimum and maximum frequencies were 0.12 and 4.04 kHz, respectively. It was not revealed by cluster analysis, accounting for only 1% of cluster 51.

GROUP 6.

Class 6a. There was only one class (6a) in this group. These sounds were noisy, without a tonal component or a clear pulsive structure (Figure 28). Their spectrograms looked like blows (class 1a) that lacked their tonal component, but aural impressions did not corroborate this possibility. They were broadband: the frequency range had a mean of 3.77 kHz, with a mean minimum and maximum frequencies of 0.21 and 3.98 kHz, respectively (Table 13). Mean duration was 0.31 sec. Peak frequency was difficult to assess, because of the noisy nature of these sounds. The means obtained for the three sampling points were 1.21, 0.59 and 2.2 kHz.

With two sounds, class 6a ranked only thirty-seventh in the sample. They were found in clusters 51 and 61, where they accounted for only 1.4 and 0.5% of the cluster respectively. They were not recognized by cluster analysis, but because of their relatively long duration and broad bandwidth, the relative weight of the additional variables dealing with their exclusively noisy nature was low.

GROUP 7.

All the classes in group 7 had a mean bandwidth of at least 2 kHz. They were pulsive, although pulse rate was variable between and sometimes within classes. Often, peak frequency, repetition rate, bandwidth, or a combination of them increased toward the end of the sounds. Noise was common in all but class 7h. Duration was variable between classes, and in some cases, within classes as well. Mean duration was in the 0.23-1.33 sec range (Table 14). There were seven classes in this group.

Table 13. Characteristics and clustering of the single class in group 6.

For each class, the number of cases (n), mean dominant frequency at three points (start, middle, and end of sound), minimum and maximum frequencies, and duration are given, with the standard deviation in brackets. Structure of the sounds and the number of clusters of each type are also shown. The highest proportion (%) of the class found in a single cluster is in brackets, below the appropriate cluster type.

CLASS (n)	DOMINANT FREQ (kHz)			MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)	STRUCTURE *	CLUSTER TYPE **					
	START	MIDDLE	END					A	B	C	D	E	F
6a (2)	1.21 (0.56)	0.59 (0.33)	2.20 (0.91)	0.21 (0.11)	3.98 (0.15)	0.31 (0.20)	N					2 (50)	

* Structure types are as in Table 6, p. 64.
** Cluster types are described in Table 5, p. 62.

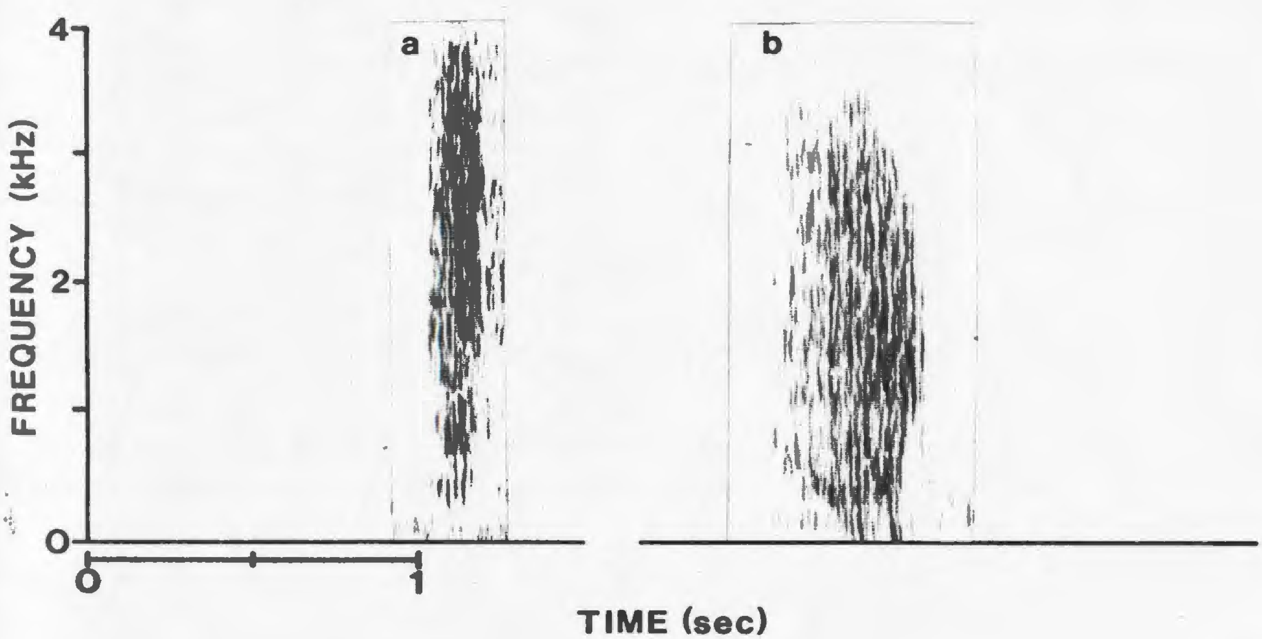


Figure 28. Spectrograms of class 6a sounds. a is from cluster 51; b is from cluster 61. Analysis filter and breaks in abscissa are as in Figure 6, p. 67.

Table 14. Characteristics and clustering of the seven classes in Group 7.

For each class, the number of cases (n), mean dominant frequency at three points (start, middle, and end of sound), minimum and maximum frequencies, and duration are given, with the standard deviation in brackets. Structure of the sounds and the number of clusters of each type are also shown. The highest proportion (%) of the class found in a single cluster is in brackets, below the appropriate cluster type.

CLASS (n)	DOMINANT FREQ (kHz)			MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)	STRUCTURE *	CLUSTER TYPE **					
	START	MIDDLE	END					A	B	C	D	E	F
7a (57)	1.29 (0.69)	0.82 (0.61)	1.06 (0.63)	0.15 (0.06)	4.15 (1.68)	0.25 (0.10)	SFN		1				6 (40)
7b (1)	1.75 -	1.09 -	1.45 -	0.30 -	7.79 -	0.45 -	F				1 (100)		
7c (99)	0.23 (0.18)	0.31 (0.11)	0.77 (0.47)	0.13 (0.03)	3.28 (1.98)	0.24 (0.09)	F(STN)	1 (90)		1			3
7d (194)	0.41 (0.44)	0.32 (0.32)	0.87 (0.52)	0.13 (0.03)	3.54 (1.81)	0.55 (0.22)	SF(N)	1 (72)		5			5
7e (17)	1.02 (0.52)	1.03 (0.50)	0.94 (0.56)	0.13 (0.01)	3.53 (1.16)	1.02 (1.75)	S(N)			4			4 (41)
7f (3)	1.31 (0.45)	1.00 (0.13)	1.65 (0.37)	0.37 (0.24)	4.87 (1.58)	0.46 (0.25)	SN						3 (33)
7g (1)	2.88 -	0.37 -	1.71 -	0.12 -	3.76 -	1.33 -	SF					1 (100)	

* Structure types are as in Table 6, p. 64.
** Cluster types are described in Table 5, p. 62.

<u>Class 7a.</u> These sounds started with a pulsive portion of relatively high frequency (mean peak frequency at the beginning was 1.29 kHz, Table 14) and slow repetition rate (Figure 29). The middle section had lower frequencies. Peak frequency was also lower there: 0.82 kHz. Peak frequency then went up again in the last part of the sounds, for a mean of 1.09 at the end. Repetition rate was faster in the second half of the sounds, where a harmonic structure usually took place (Figure 29). Bandwidth, which averaged 4.00 kHz, was also at its maximum in the second half. Mean minimum frequency was 0.15 kHz, while mean maximum frequency reached 4.15 kHz. Duration averaged 0.25 sec. Acoustic properties of class 7a were intermediate between those of classes 5b and 7c. In fact, these sounds were very much like those of class 7c (Figure 31), with the addition of a pulsive prefix of higher frequency and slower repetition rate.

Class 7a had 57 sounds and was the seventh largest in the sample. It was not very well defined by cluster analysis. Cluster 54, type "B", contained 16 of these sounds, which is 28% of the class and 62% of the cluster. But the highest number of these sounds came from a type "F" cluster, cluster 51 (23 cases, or 40%), where they accounted for only 33% of the cluster. One to eight cases were found in each of clusters 50, 56, 57, 61 and 81.

As seen before, cluster 51 also contained many class 5b sounds. This is because these two classes were very similar after digitizing: the difference between the two was mainly based on the frequency of peak energy at the beginning, presence or absence of a terminal frequency upsweep and on the presence or absence of an increase in the repetition

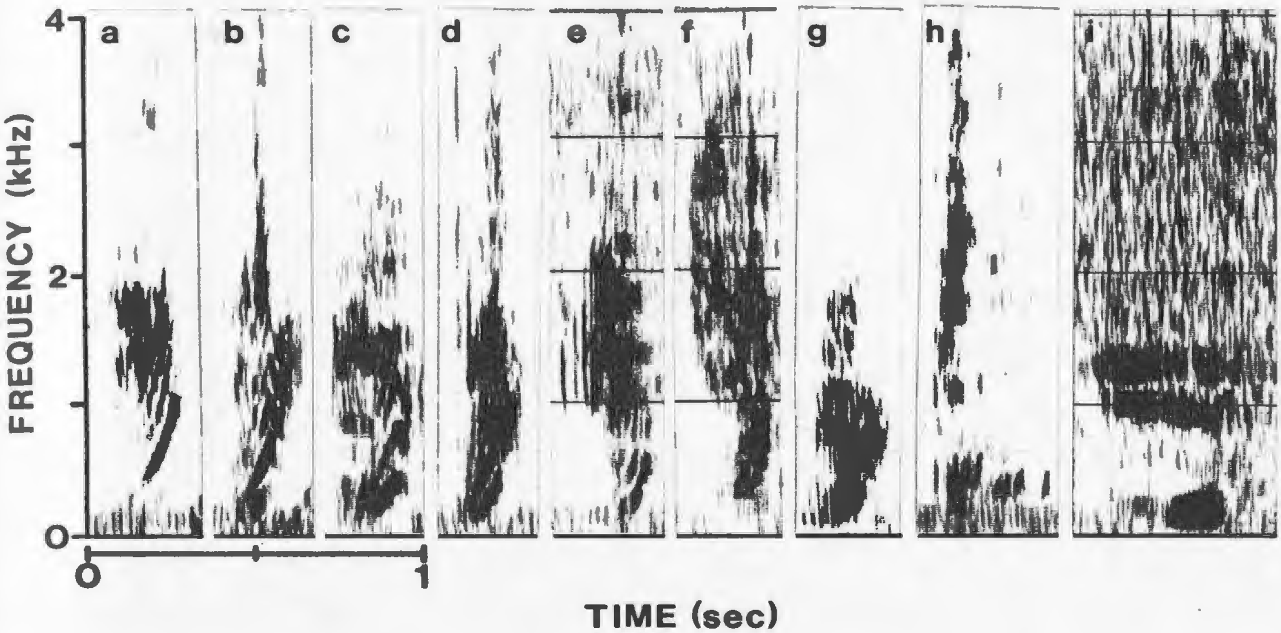


Figure 29. Some spectrograms of class 7a sounds. a-d are from cluster 51; e-f from 54; g-h from 57; i from 61. Analysis filter and breaks in abscissa are as in Figure 6 p. 67.

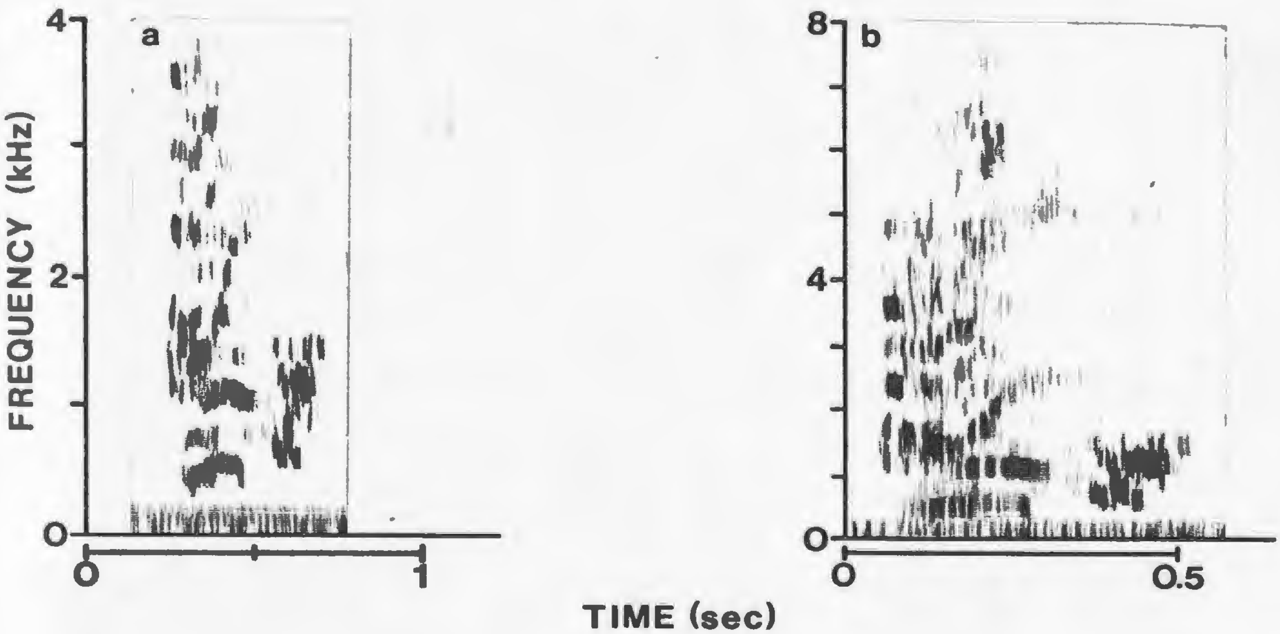


Figure 30. Spectrograms of class 7b sound. a and b are the same sound, from cluster 52. Analysis filter is as in Figure 6 p. 67.

rate toward the end of the sound. These factors were not well represented in the data. Sounds in cluster 54 lasted in average longer than those from cluster 51 (0.26 vs 0.22 sec, Appendix D), had a higher peak frequency in the middle (1.47 vs 0.48 kHz) and a lower peak frequency at the end (1.00 kHz vs 1.43). The few sounds found in other clusters were shorter (0.08 and 0.18 sec in clusters 56 and 50, respectively) or longer (0.51 and 0.79 sec in clusters 61 and 81) than average for the class, while those in clusters 57 and 61 had narrower bandwidth (3.05 and 2.94 kHz, respectively, against 4.03 and 3.95 kHz in clusters 51 and 54).

Class 7b. This sound was similar to those of classes 5b and 7a, but sounded very different. It was pulsive, and the repetition rate was too fast to discern the individual components with a filter of 150 or even 300 Hz. The harmonic structure was very irregular (Figure 30). The beginning of the sound had its energy spread over 4 kHz, with a peak frequency of 1.75 kHz (Table 14). The frequency range was still broader in the middle of the sound, being near the maximum of 7.49 kHz, but the peak frequency was lower: 1.09 kHz. The sound was much narrower in the end, and the peak frequency was 1.45 kHz. Minimum and maximum frequencies were 0.3 and 7.79 kHz respectively. With a duration of 0.45 sec, it was almost twice as long as the average sound from class 7a. This sound was unique in the sample, and not well revealed by cluster analysis. It was placed in a small cluster, 52 (n=4). Two of its elements were from class 5b.

Class 7c. Class 7c sounds were relatively short, with a mean duration of 0.24 sec (Table 14). The peak frequency of these sounds increased from the beginning to the end, passing from 0.23 kHz to 0.31

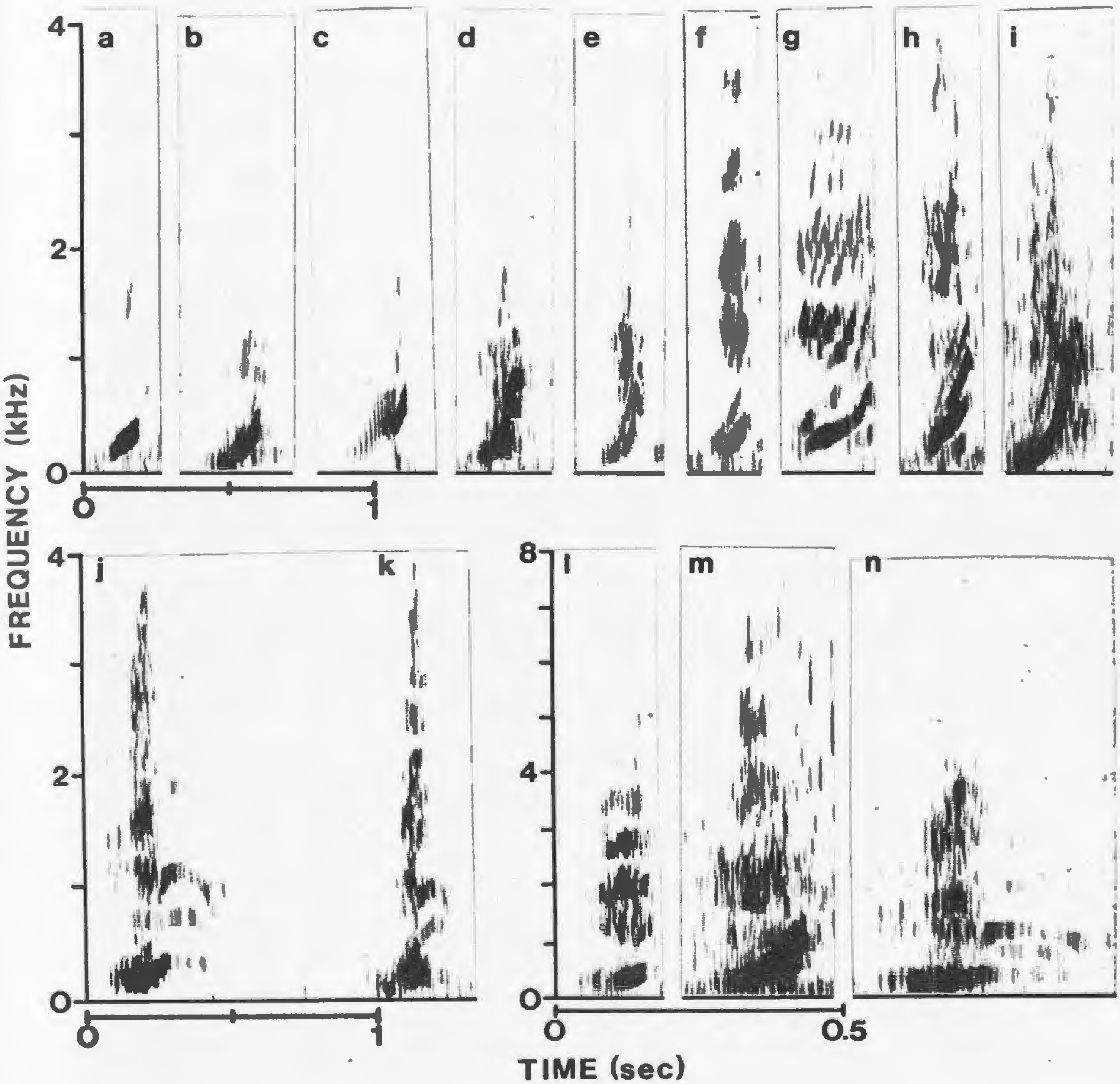


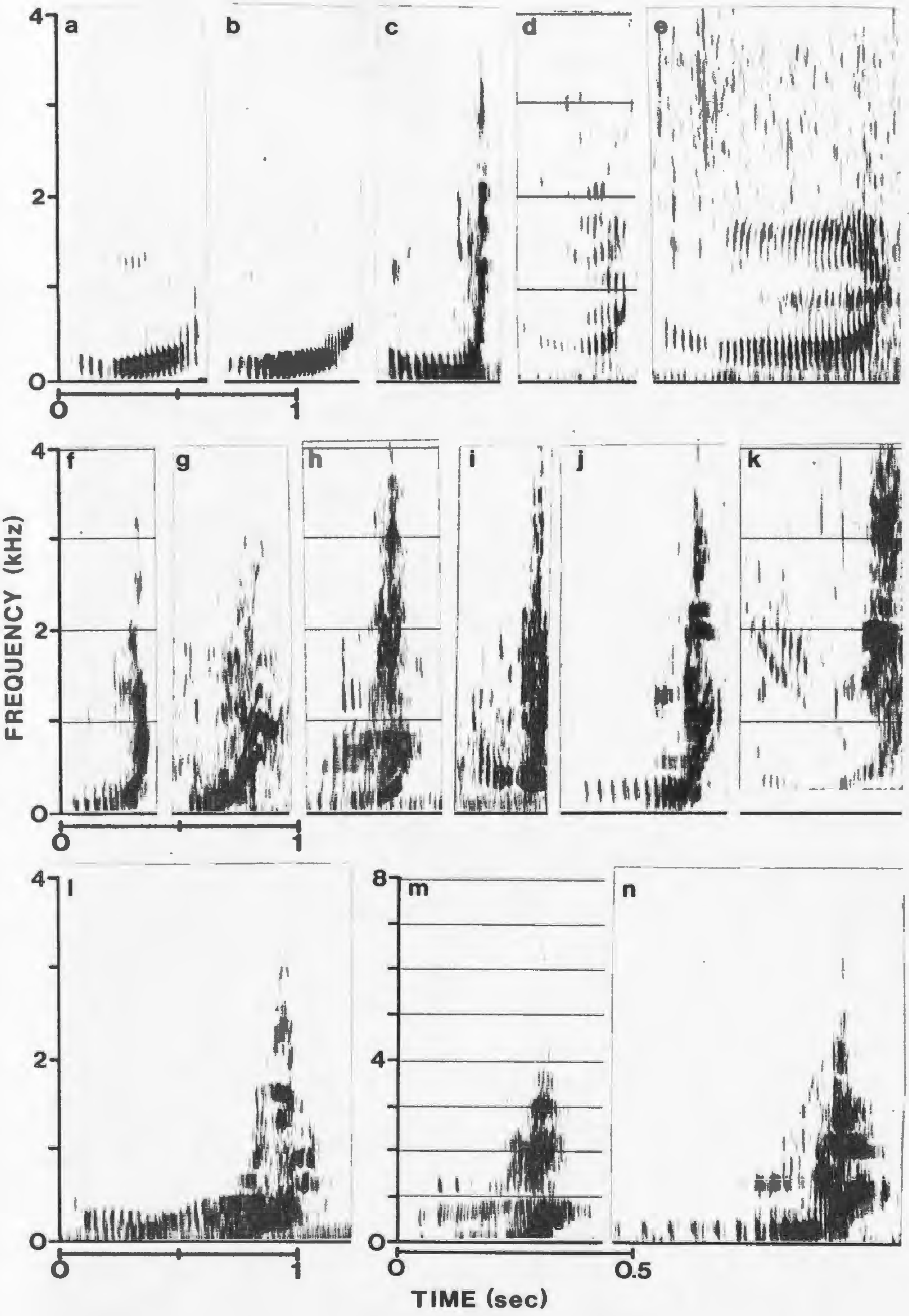
Figure 31. Some spectrograms of class 7c sounds. f and l are the same sound, as well as h and m, and j and n. a is from cluster 58; b-f, h-n are from 57; g is from 51. Analysis filter and breaks in the abscissa are as in Figure 6, p. 67.

kHz at the middle and then 0.77 kHz. Bandwidth also increased toward the end of the sounds, giving them a typical "J" shape (Figure 31). Bandwidth was very variable between sounds. The simplest forms had energy on not more than 0.38 kHz, while the other extreme had energy on the totality of the bandwidth studied (0.12-8 kHz). The reason for this was the relative abundance of high frequency noise: those sounds with little noise were probably produced by distant whales. Overall, bandwidth averaged 3.15 kHz. These sounds were pulsive, the repetition rate being sometimes slow enough at the beginning to distinguish the individual clicks. But a harmonic structure was almost always present near the middle of the sounds. Repetition rate generally increased with time, which was seen as an increase in the spacing between harmonics on the spectrograms. Some cases had a tonal ending. Minimum and maximum frequencies averaged 0.13 and 3.28 kHz, respectively. This class corresponds to the sounds described as "yup" in Winn <u>et al</u>. (1979), except that they usually reach higher frequencies in the present study.

With 99 sounds, it was the fifth most important class in the sample. The majority (89 cases, or 90%) were from cluster 57, which was of type "A" (55% of its members were in class 7c). Three others were in cluster 58, which had only four cases. Their duration and bandwidth was much less: 0.15 sec and 1.22 kHz, vs 0.23 sec and 3.05 kHz in cluster 57. Three cases came from cluster 51, three from cluster 61, and one from cluster 1. They constituted a minor part of these clusters.

Class 7d. These sounds had a variable duration, but the average was more than half a second (0.55 sec, Table 14). They were pulsive, and at first repetition rate was slow: each subunit was readily visible on the spectrograms (Figure 32). Bandwidth was usually narrower in this

Figure 32. Some spectrograms of class 7d sounds. k and m are the same sound, as well as j and n. a-c, f-h, j and m-n are from cluster 61; d is from 57; e and l from 69; i from 63; k from 60. Analysis filter and breaks in abscissa are as in Figure 6, p. 67.


a
b
c
d
e
f
g
h
i
j
k
l
m
n
4
2
0
8
FREQUENCY (kHz)
1
0.5
TIME (sec)

part of the sound: most cases had little energy above 0.5 kHz. Also, frequency was low at the beginning, where the minimum frequency of the sound (mean of 0.13 kHz) was usually found. Peak frequency increased toward the end of the sound: it averaged 0.41 kHz at the beginning, 0.32 kHz at the middle, and 0.87 kHz at the end. Maximum frequency averaged 3.54 kHz and was found in the second half of the sounds. Bandwidth and, often, repetition rate also increased at the end of these sounds. Many cases ended with a complex harmonic structure, because of the fast repetition rate. The last section of these sounds looked much like class 7c sounds (Figure 31, p. 119). In some sounds however, repetition rate increased only slightly or not at all. The individual components were still distinguishable on the spectrograms (Figure 32a-e). In fact, many intermediates were found, and all these sounds were put in the same class. Bandwidth averaged 3.41 kHz, and was often broader for those sounds ending with a faster repetition rate. The spectrograms of class 7d sounds were similar to the "type 1" category of Lawton (1979), and to the "pulsive moan-yup" sounds of Winn et al. (1979).

Class 7d had 194 cases and was the largest in the repertoire. It was well discriminated by cluster analysis. Most of the cases (139 or 72%) came from a single cluster, 61. This cluster was the largest obtained, with 201 elements, and 70% of them were in class 7d.

The next largest concentration (23 or 12%) was found in cluster 57, with most of class 7c. They were the shortest cases of the class, the section of relatively low, constant frequency being scarcely noticeable. Average duration was only 0.23 sec in cluster 57, vs 0.51 sec in cluster 61 (Appendix D). Five type "C" clusters also contained these sounds. Sixteen cases (8%) were found in cluster 69, accounting for 55% of the cluster. They were longer than average, with a mean duration of 0.94 sec in this cluster. Mean bandwidth was also slightly less (2.27 kHz). The three elements of cluster 59 all belonged to class 7d. They were extremely long (mean of 1.12 sec), and had a broad bandwidth (7.89 kHz). In two of them, a second band of energy was also present above the low frequency clicks of the sounds' first section. The only sound found in cluster 60 was also long (0.73 sec). The clicks in the first part of the sound had energy in the normal range (around 0.3 kHz), but also in the 1.5-2 kHz range, with the peak in the later (Figure 32k). The two sounds in cluster 62 were also fused to class 7d. They very similar to the other members of the class, with a slightly higher minimum frequency (0.22 kHz), which affected greatly the similarity coefficient, because of the logarithmic frequency scale. Peak frequency was lower at the end than at the middle (0.87 vs 1.57 kHz), because of a second band of energy in the middle section of the sounds. Cluster 63, with three cases, was also fused to this class. These sounds were a bit shorter than the average for the class (0.45 sec), and had a broad bandwidth (4.98 kHz). One of the four sounds in cluster 80 was included. Mean duration was 0.57 sec in this cluster, while mean bandwidth was 4.12 kHz. A few other cases (1-3) were found in clusters 51, 82 and 83, but were among many sounds of other types.

<u>Class 7e.</u> These sounds were pulsive, with a slow and relatively constant repetition rate (Figure 33). They were very similar to some sounds from the previous class, with a band of very high intensity between 0.5 and 2 kHz. This was reflected in the measurements of peak frequency: 1.02, 1.03 and 0.94 kHz at the three sampling points (Table 14). As indicated in these measurements, frequency decreased toward the

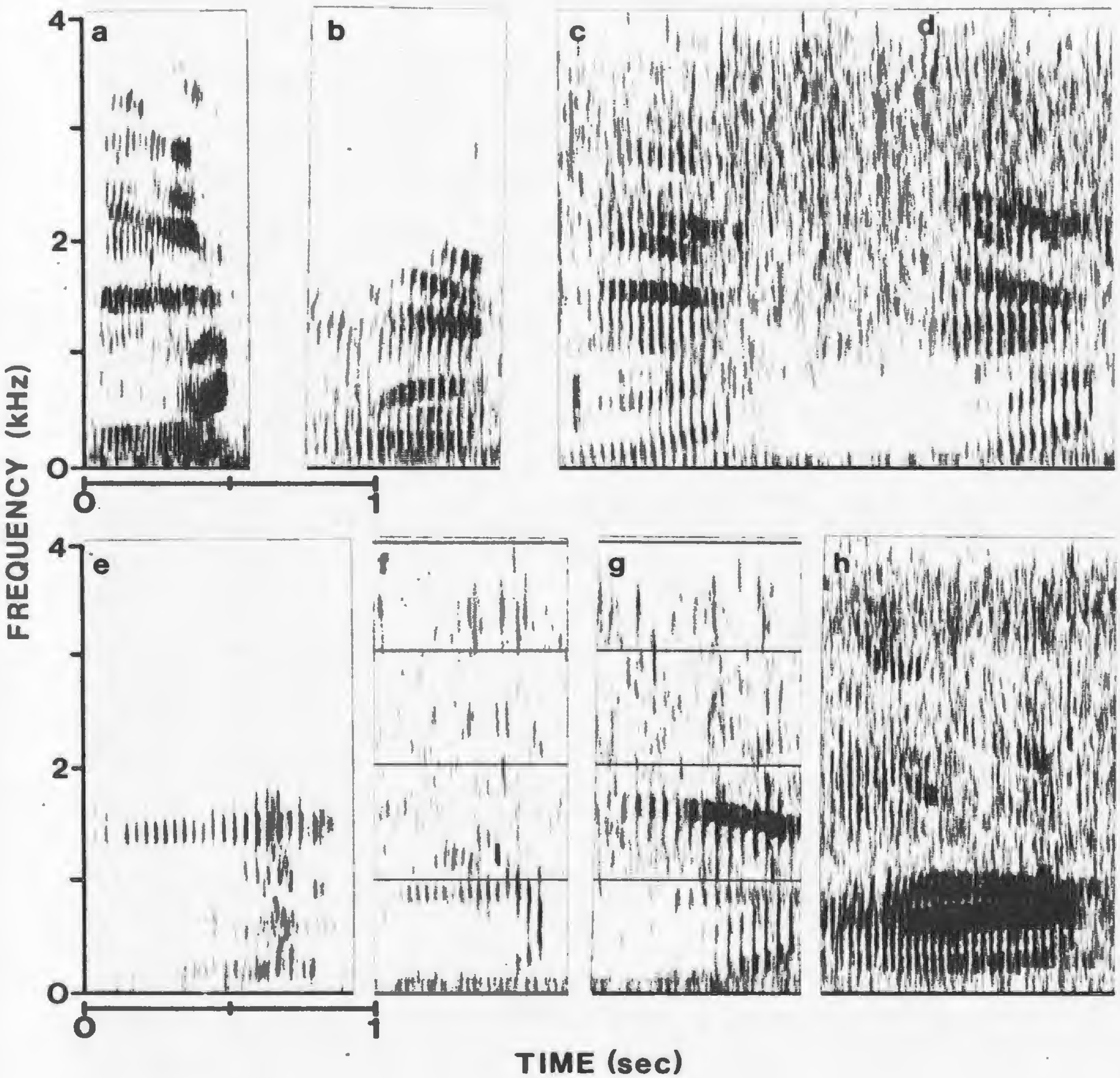


Figure 33. Some spectrograms of class 7e sounds. a-d are from cluster 61; e is from cluster 65; f from 66; g from 67; h from 83. Analysis filter and breaks in the abscissa are as in Figure 6, p. 67.

end of the sounds in this band of high amplitude. Often, there was a second band of high energy at lower frequencies, which rose at the end (Figure 33), like in class 7d. The average bandwidth was 3.4 kHz. Mean minimum frequency was 0.13 kHz, and mean maximum frequency reached 3.53 kHz. Duration averaged 1.02 sec, but the presence of an extremely long case (7.8 sec) was the main reason for such a high average.

Class 7f had seventeen cases and was the twentieth largest in the sample. It was split in many clusters. Cluster 61 had the highest number (7 or 41%) but contained many sounds of other classes as well: class 7e accounted for only 4% of the cluster, which was of type "F". However, four small clusters contained mostly sounds of this class: clusters 64-67. Clusters 14, 70 and 83 had one or two sounds each in class 7e, and were of type "F". There were differences in duration, bandwidth, and peak frequencies between these clusters. Sounds in clusters 61 and 64-67 had a mean bandwidth below 3 kHz, while it was 6.24 kHz in cluster 14. Mean duration was below 0.6 sec in clusters 14, 61 and 64, and 3.32 sec in cluster 70. Also, mean peak frequencies were below 1 kHz in clusters 61, 66, 70 and 83, while at least one of the three measurements had an average value of 1.4 kHz or higher in the other clusters (Appendix D). Mean characteristics of type "F" clusters are not necessarily relevant however. For example, dominant frequency was above 1 kHz in Figure 33a-d, which came from cluster 61.

<u>Class 7f.</u> These pulsive sounds had most of their energy in the 1-3 kHz band (Figure 34). Minimum and maximum frequencies averaged 0.37 and 4.87 kHz respectively, for a mean bandwidth of 4.5 kHz. Mean peak frequency was 1.31 kHz at the beginning, 1.00 kHz at the middle, and 1.65 kHz at the end. The repetition rate was slow enough to discrim-

inate each subunit. Important characteristics of this class were the irregular sound intensity and peak frequency.

This small class (3 cases) ranked thirty-third in size. It was not recognized by cluster analysis: each case was in a different type "F" cluster: 51, 61 and 81. Because sound intensity was not coded, and peak frequency only coarsely coded, these sounds were clustered with sounds of similar frequency contour, although they sounded different to a human listener.

Class 7g. This class was pulsive, and the repetition rate increased with time (Figure 35). Much noise was also present. Duration was 1.33 sec (Table 14), and the bandwidth 3.64 kHz. Peak frequency measurements were 2.88, 0.37 and 1.71 kHz, but they were not representative of this class. In fact, peak frequency was in the 0.3-0.8 kHz for most of the sound. But this component was faint at the beginning of the sound, and the measurement of peak frequency was taken on high frequency noise. Similarly, the last third was faint and did not contain any energy in the frequencies that were most represented in the main part of the sound. Minimum and maximum frequencies averaged 0.12 and 3.76 kHz respectively, but there was little energy above 1.5 kHz.

There was only one sound in this class. It was not recognized by cluster analysis: it was found in cluster 82, but accounted for only 5% of the cluster.

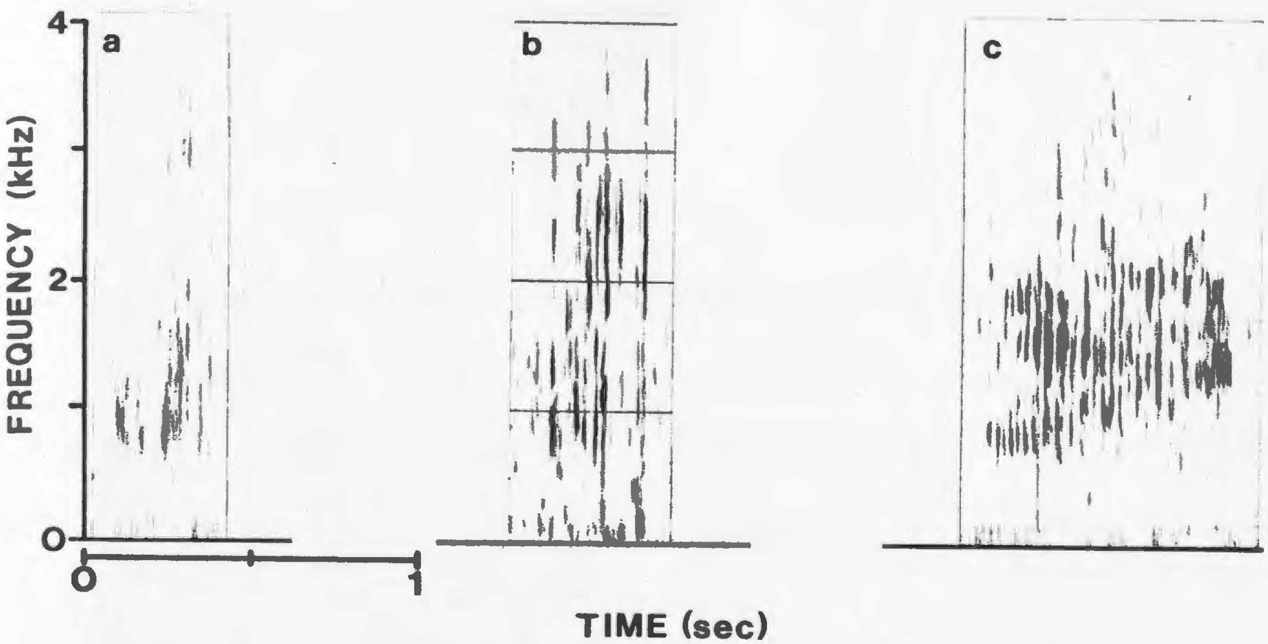


Figure 34. Spectrograms of class 7f sounds. a is from cluster 51; b from cluster 61; and c from cluster 81. Analysis filter and breaks in the abscissa are as in Figure 6, p. 67.

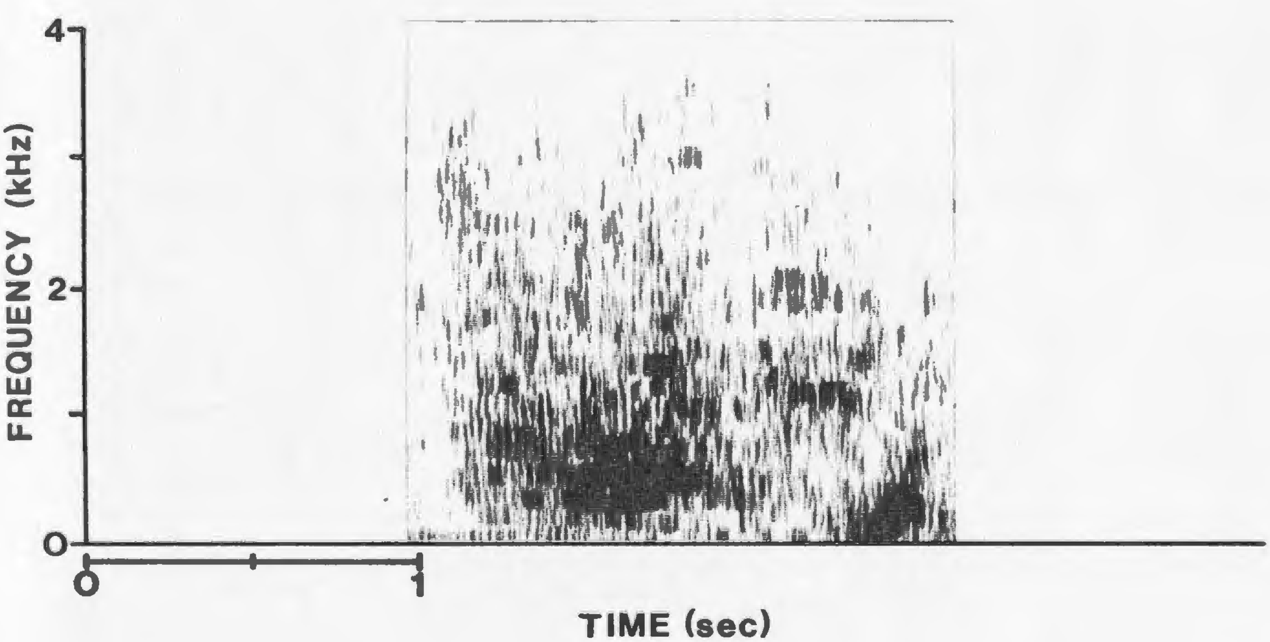


Figure 35. Spectrogram of class 7g sound, which is from cluster 82. The 0-1 kHz sound in the extreme right of the spectrogram does not belong to the class 7g sound. Analysis filter is as in Figure 6, p. 67.

Table 15. Characteristics and clustering of the six classes in Group 8.

For each class, the number of cases (n), mean dominant frequency at three points (start, middle, and end of sound), minimum and maximum frequencies, and duration are given, with the standard deviation in brackets. Structure of the sounds and the number of clusters of each type are also shown. The highest proportion (%) of the class found in a single cluster is in brackets, below the appropriate cluster type.

CLASS (n)	DOMINANT FREQ (kHz) START	MIDDLE	END	MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)	STRUCTURE *	CLUSTER TYPE ** A	B	C	D	E	F
8a (49)	0.38 (0.31)	0.25 (0.10)	0.44 (0.35)	0.13 (0.01)	1.86 (1.37)	0.72 (0.38)	S			1		1 (61)	4
8b (21)	0.47 (0.44)	0.44 (0.26)	0.46 (0.43)	0.14 (0.02)	2.80 (0.89)	2.24 (1.86)	S(FN)	1 (62)		1			4
8c (5)	0.54 (0.67)	0.57 (0.59)	0.44 (0.23)	0.14 (0.04)	4.13 (2.71)	2.82 (0.59)	F(SN)			1		1 (80)	
8d (5)	0.29 (0.14)	0.23 (0.05)	0.23 (0.07)	0.14 (0.01)	0.80 (0.81)	2.09 (1.55)	(TS)			1		1 (60)	
8e (7)	0.35 (0.16)	0.21 (0.12)	0.24 (0.18)	0.13 (0.01)	1.41 (1.22)	0.38 (0.26)	(FTS)					1 (57)	2
8f (4)	0.83 (0.43)	0.82 (0.68)	0.25 (0.07)	0.16 (0.03)	1.91 (0.27)	0.71 (0.05)	F					1 (50)	2

* Structure types are as in Table 6, p. 64.
** Cluster types are described in Table 5, p. 62.

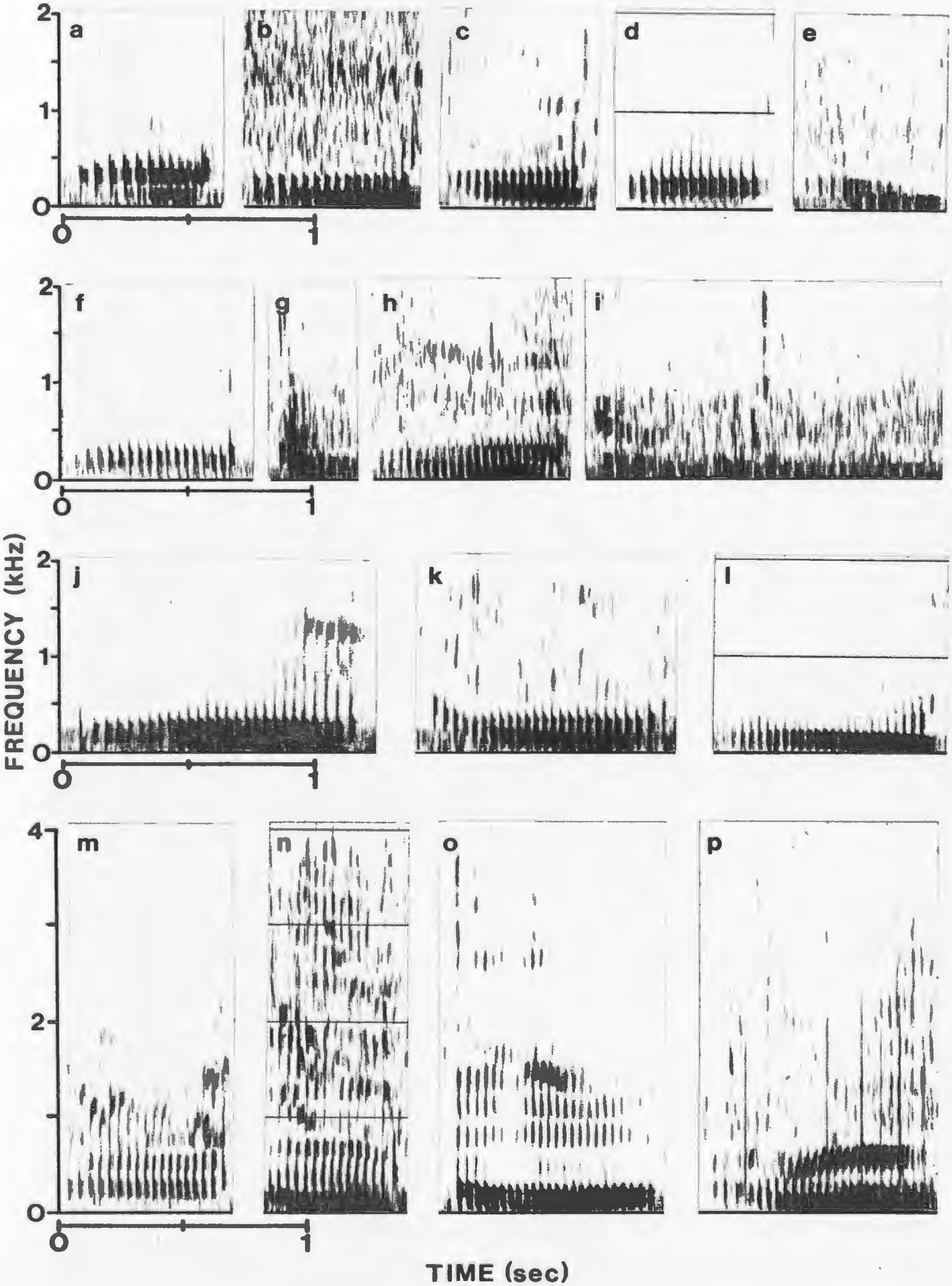
GROUP 8.

With the exception of class 8e, in which some cases were tonal, sounds in this group were pulsive. The repetition rate was variable, but in most cases it was slow enough to allow for distinction of the individual clicks. Most of the energy was below 1 kHz, and duration was over 0.71 sec for all but one class (Table 15). There were six classes in this group.

Class 8a. These pulsive sounds were long, with a mean duration of 0.72 sec (Table 15). Repetition rate and peak frequency were relatively constant (Figure 36). The individual subunits of these sounds were always easy to discriminate, while peak frequency averaged 0.38, 0.25 and 0.44 kHz at the three sampling points. Minimum and maximum frequencies averaged 0.13 and 1.86 kHz respectively, for a bandwidth of 1.73 kHz. The highest intensity was in the 0-0.5 kHz region of the spectrum. This class seems to be equivalent to the "pulsive moans" of Winn et al. (1979).

Class 8a had 49 cases and ranked eighth in size. It was not distinguished from classes 7d by cluster analysis: 30 cases (61%) came from cluster 61. This represented 15% of the sounds in this cluster. This was probably because repetition rate was not included in the data, while sound intensity and frequency modulation were only imperfectly coded. The second highest concentration was in cluster 69: 11 cases (22% of the class; 38% of the cluster). Here again, the rest of the cluster was mostly made up of class 7d sounds (16 cases). Mean duration was 0.94 sec in cluster 69 (Appendix D), which is above the average duration for the class (Figure 36h,j-l). Cluster 74 had only one case (Figure 36i). It was longer than average (1.36 sec) and characterized by a decreasing

Figure 36. Some spectrograms of class 8a sounds. a-g and m-n are from cluster 61; h and j-l are from 69; i is from 74; o-p are from 83. Analysis filter and breaks in abscissa are as in Figure 6, p. 67.


a
b
c
d
e
f
g
h
i
j
k
l
m
n
o
p
FREQUENCY (kHz)
0
1
2
4
TIME (sec)

dominant frequency (0.72 kHz at the beginning, 0.17 at the middle and 0.12 at the end, Appendix D). A few more cases were found in clusters 70, 82-83 which were all of type "F" relative to class 8a. Very long duration or/and broad bandwidth (clicks sometimes had energy over many kHz, even if the peak frequency was in the 0.3 kHz range) were probably responsible for this scattering.

<u>Class 8b.</u> These sounds were also pulsive and had low dominant frequencies. Average duration was much longer however (2.24 sec, Table 15), although very variable; mean bandwidth was broader (2.66 kHz), but there was little energy above 1 kHz. Most cases were also characterized by an increasing repetition rate (Figure 37). Each click was recognizable at the beginning of the sounds, but usually it was replaced by side bands toward the end. Minimum and maximum frequencies were 0.14 and 2.80 kHz, respectively. Peak frequency averaged 0.47 kHz at the beginning, 0.44 kHz at the middle and 0.46 kHz at the end. This class could be seen as the juxtaposition class 8a and 8f (Figures 36 and 41). It was described as a "ratchet" sound by Beamish (1979).

There were 21 cases in class 8b, which ranked seventeenth in size. It was relatively well discriminated by cluster analysis. Thirteen cases (62%) came from cluster 70 (type "A") or 50% of the cluster. One of the two sounds in cluster 71 belonged to class 8b. The other cases came from clusters 61, 69, 82 and 83. Duration was shorter than 0.1 sec in clusters 61, 69 and 83, between 1-2 sec in clusters 71 and 82, and 3.32 sec in cluster 70 (Appendix D). Differences in bandwidth were probably also responsible for this splitting: bandwidth was less than 3 kHz in clusters 61, 69 and 71, and between 3-5 kHz in the other clusters.

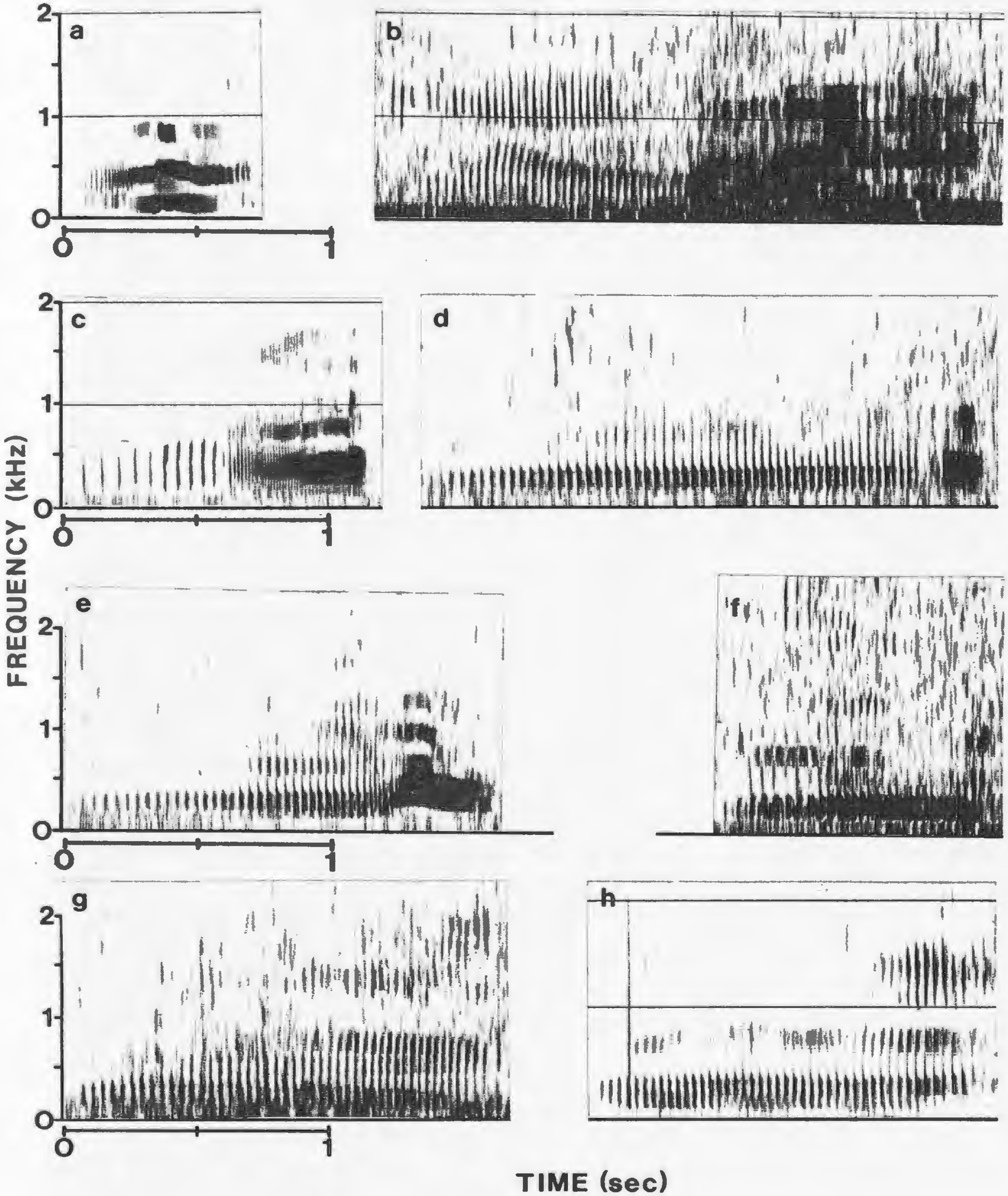
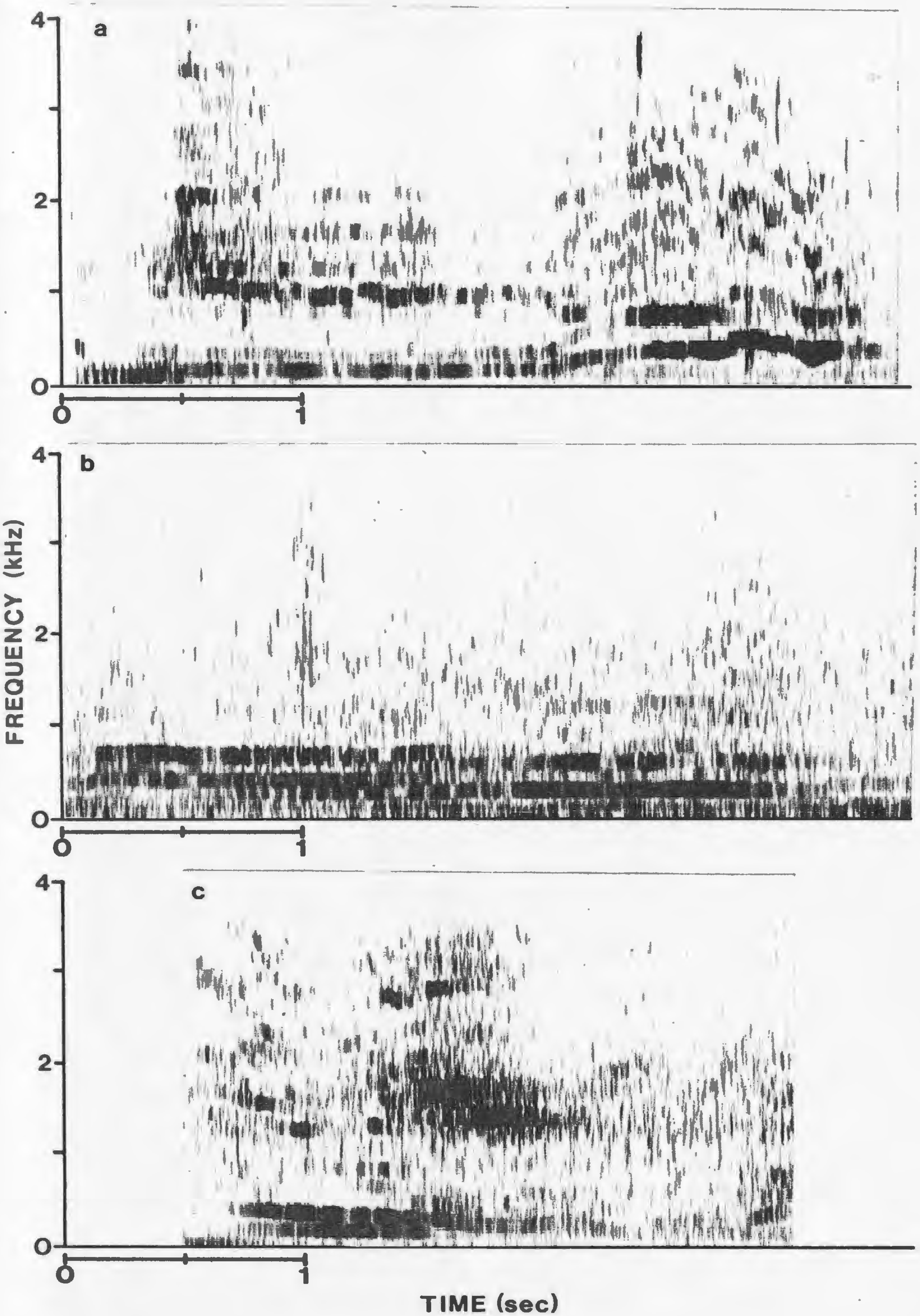


Figure 37. Some spectrograms of class 8b sounds. a is from cluster 61; b, d-e and h are from cluster 70; c is from 69; f from 83; g from 82. Analysis filter and breaks in the abscissa are as in Figure 6, p. 67.

Figure 38. Some spectrograms of class 8c sounds. All three are from cluster 70. Analysis filter is as in Figure 6, p. 67.



a
b
c
4
2
0
0
1
FREQUENCY (kHz)
TIME (sec)

Class 8c. In this class, repetition rate and sound intensity varied frequently and in an unpredictable manner (Figure 38). Pulse rate was almost always too fast for aural or spectrographic discrimination of the subunits. Most of the energy was below 1 kHz, but higher bands were sometimes present, leading to a mean bandwidth of 3.99 kHz (Table 15). Minimum and maximum frequencies averaged 0.14 and 4.13 kHz, respectively. These sounds were very long (mean of 2.82 sec). An increase in peak frequency and pulse rate was present at the end for two of the sounds, but peak frequency was about constant for the class: 0.54, 0.57 and 0.44 kHz.

There were only five cases in class 8c, which ranked twenty-sixth in size. One was found alone in cluster 72 (type "C"), while the four others came from cluster 70, which also included most of class 8b. This is because the distinction between these two classes was based largely on repetition rate and amplitude modulation, which resulted in very different aural impressions.

Class 8d. These sounds were characterized by a very narrow bandwidth (0.66 kHz) and a low and constant peak frequency: 0.29, 0.23 and 0.23 kHz (Table 15). They lasted an average of 2.09 sec. Minimum and maximum frequencies averaged 0.14 and 0.8 kHz. Some were tonal, others pulsive with a repetition rate sufficiently slow to distinguish the narrow clicks that composed it (Figure 39).

Class 8d had five members, ranking twenty-sixth in the data set. The two shortest sounds of the class were found in cluster 73, which contained only these two sounds. The other three (60%) were in cluster 70, accounting for only 12% of the cluster.

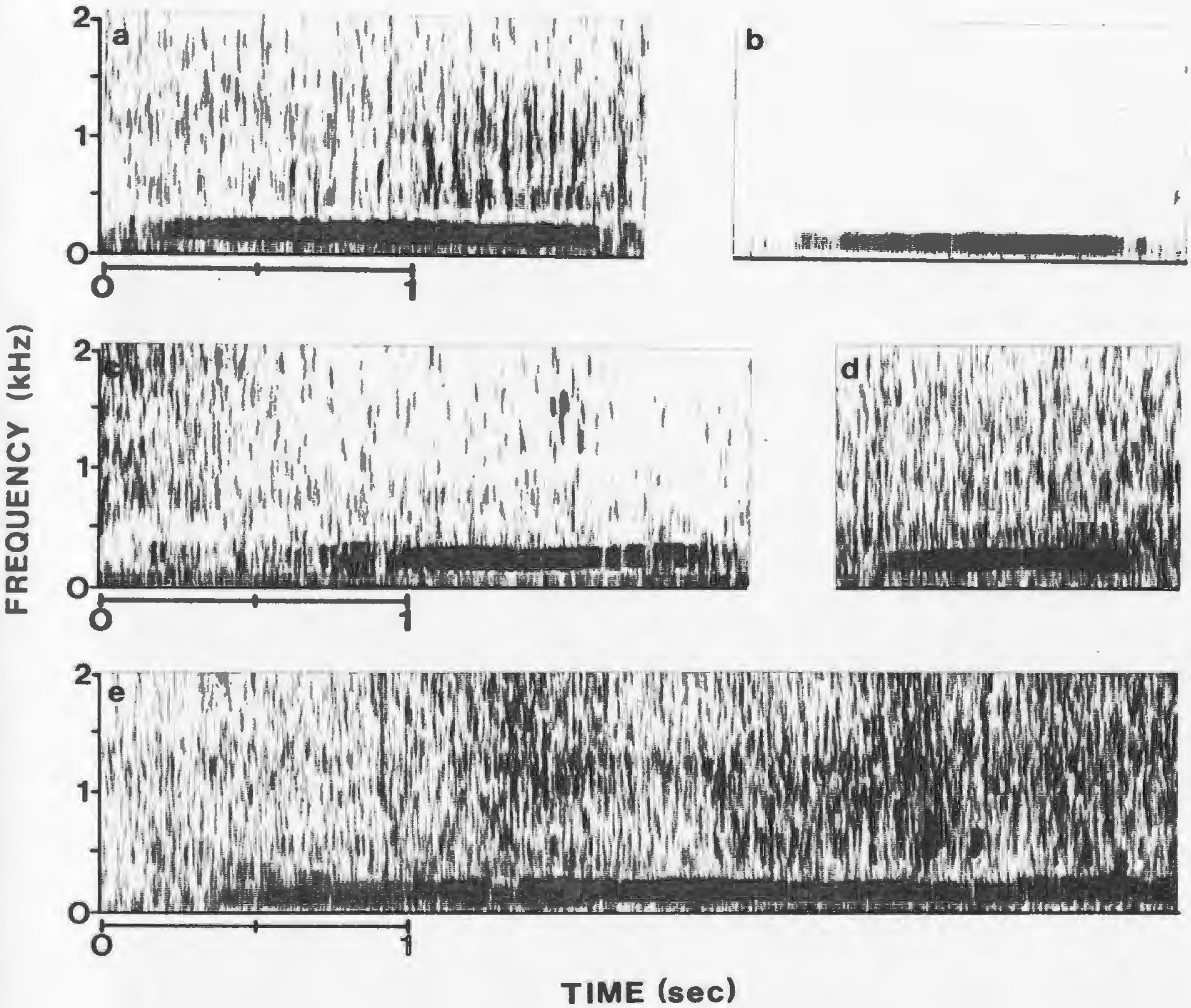


Figure 39. Spectrograms of class 8d sounds. The few clicks in the 0.5-1.5 kHz range of a are not part of the sound. a, c and e are from cluster 70; b and d are from 73. Analysis filter and breaks in the abscissa are as in Figure 6, p. 67.

Class 8e. This class was not homogeneous: some of its members sounded different, and their spectrograms looked different (Figure 40). In an effort to limit the number of rare types, these sounds were put together since they were pulsive and had their maximum intensity in very low frequencies (often under the lowest frequency sampled, 125 Hz, and generally below 400 Hz). Measurements of peak frequency were: 0.35, 0.21 and 0.24 kHz (Table 15). Mean duration was 0.88 sec, but was very variable. Mean bandwidth was 1.28 kHz, with a minimum frequency averaging 0.13 kHz and a maximum frequency averaging 1.44 kHz. It should be noted that measurements of minimum frequency was quite meaningless in such sounds, since frequencies below 125 Hz were digitized at 125 Hz. The pulse rate was variable, subunits being distinguishable in some cases, but not in others (Figure 40).

Class 8e had seven cases and was the twenty-fifth largest in the repertoire. Four (44%) came from cluster 57, which contained most of class 7c. They were the shortest in the class (average of 0.23 sec). The other three were in cluster 61 and had a longer duration (mean of 0.51 sec).

Class 8f. These sounds lasted in average 0.71 sec (Table 15), and had little energy above 1.5 kHz (mean bandwidth of 1.75 kHz). Minimum and maximum frequencies averaged 0.16 and 1.91 kHz. They were pulsive, with the components barely discernible or more commonly with a harmonic structure (Figure 41). Mean peak frequency was 0.83 kHz at the beginning, 0.82 kHz at the middle, and 0.25 kHz at the end.

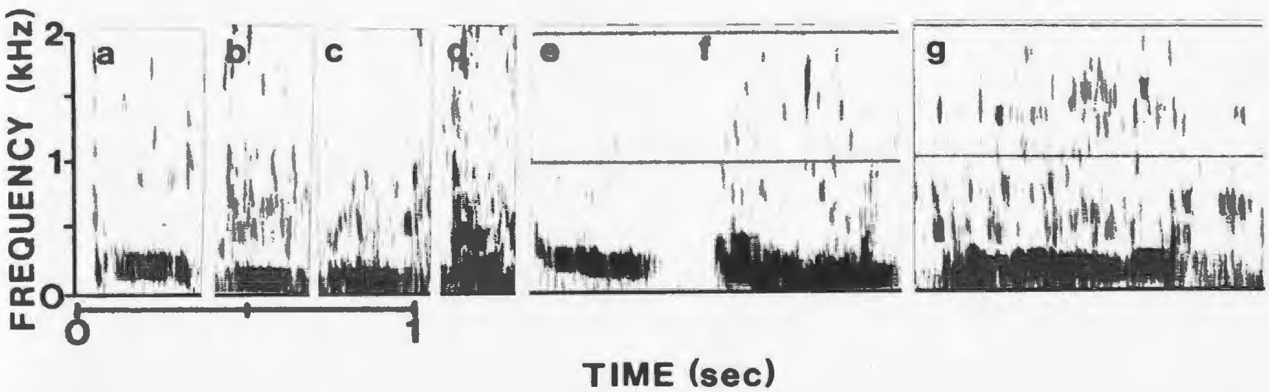


Figure 40. Spectrograms of class 8e sounds. a-d are from cluster 57; e-f are from 61; and g is from 83. Analysis filter and breaks in the abscissa are as in Figure 6, p. 67.

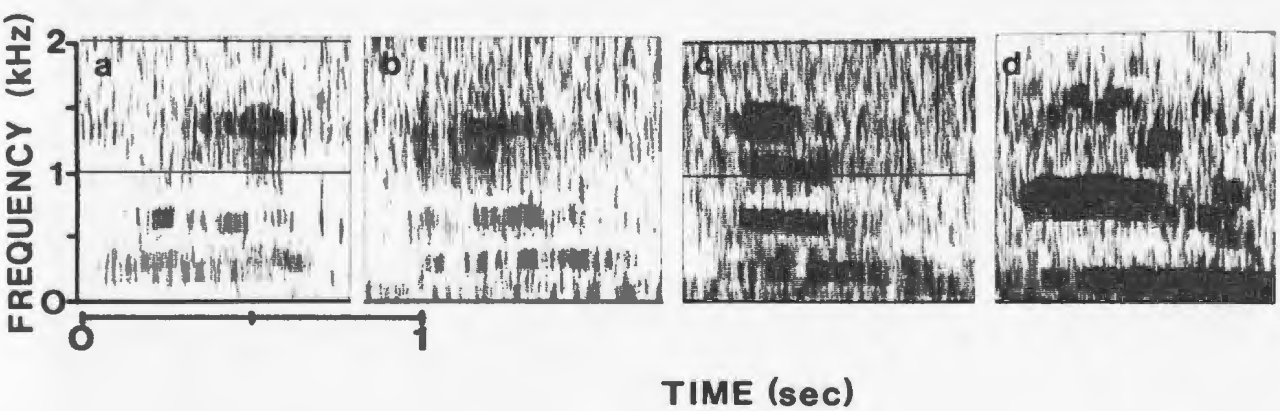


Figure 41. Spectrograms of class 8f sounds. a is from cluster 61; b is from 67; c-d are from 83. Analysis filter and breaks in the abscissa are as in Figure 6, p. 67.

Class 8f was small, having only four cases. It ranked twenty-eighth in size. It was not recognized by cluster analysis: cluster 83 had two cases, but was of type "E", while the others were in clusters 61 and 67, both of type "F". They were clustered with sounds of similar duration and frequency contour.

GROUP 9.

Class 9a. Group 9 contained only one class: 9a. These sounds were made of two or three (sometimes more) click-like structures, 0.1-0.4 sec apart (Figure 42). They seemed continuous to the human ear, even if the subunits could be heard distinctly. It might be because of the very high intensity and low frequency involved. On another hand, each subunit was very much like some class 4a sounds. Because they sounded continuous, and the pattern was so regular, these few clicks were considered a single sound and digitized accordingly.

For most sounds, the first component was a fairly broadband click with its peak energy dropping rapidly from around 1 kHz to around 0.1-0.2 kHz. For the others, one or two fainter clicks preceded the loud component just described. Peak frequency at the beginning averaged 1.18 kHz (Table 16). Most often, there was a delay of 0.1-0.4 sec between this component and the next one. This had for effect of artificially reducing the average peak frequency at the middle of the sounds to 0.17 kHz (this is because for such a long silent period in the middle of a sound, peak frequency was coded zero). The last section consisted of 1-12 clicks (usually one or two). Most of the energy was contained below 1 kHz, and the mean peak frequency was 0.64 kHz. Mean minimum and

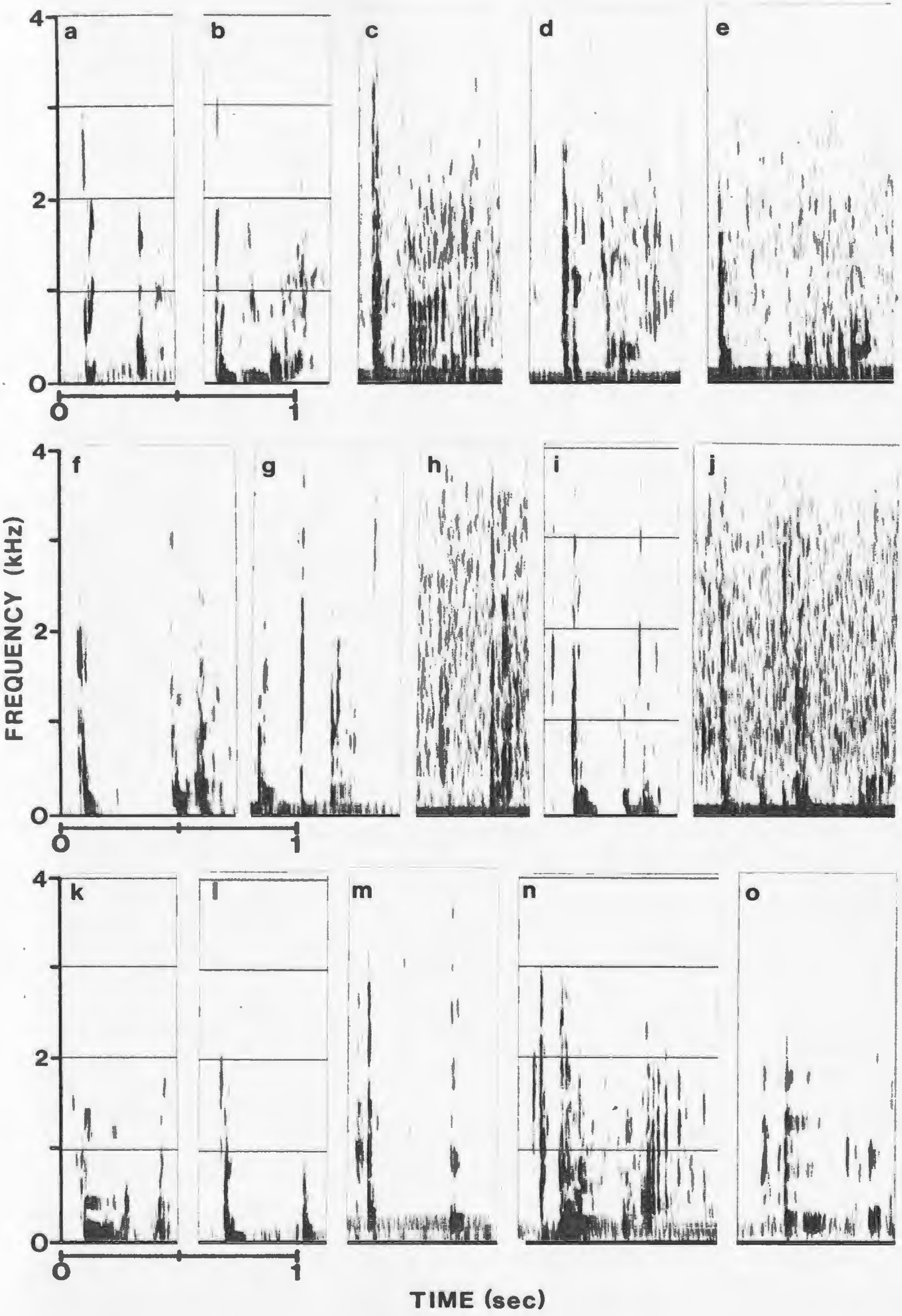
Table 16. Characteristics and clustering of the single class in Group 9.

For each class, the number of cases (n), mean dominant frequency at three points (start, middle, and end of sound), minimum and maximum frequencies, and duration are given, with the standard deviation in brackets. Structure of the sounds and the number of clusters of each type are also shown. The highest proportion (%) of the class found in a single cluster is in brackets, below the appropriate cluster type.

CLASS (n)	DOMINANT FREQ (kHz)			MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)	STRUCTURE *	CLUSTER TYPE **					
	START	MIDDLE	END					A	B	C	D	E	F
9a	1.18	0.17	0.64	0.13	3.58	0.52	TN(S)		1	5			3
(25)	(0.85)	(0.24)	(0.64)	(0.01)	(1.54)	(0.15)			(28)				

* Structure types are as in Table 6, p. 64.
** Cluster types are described in Table 5, p. 62.

Figure 42. Some spectrograms of class 9a sounds. a is from cluster 51; b-d are from 61; e-f are from 76; g is from 75; h is from 77; i is from 78; j and n are from 83; k-m are from 79; o is from 99. Analysis filter and breaks in the abscissa are as in Figure 6, p. 67.


a
b
c
d
e
f
g
h
i
j
k
l
m
n
o
4
2
0
0
1
FREQUENCY (kHz)
TIME (sec)

maximum frequencies were 0.13 and 3.58 kHz, for a mean bandwidth of 3.45 kHz. These sounds lasted an average of 0.52 sec.

Class 9a was the fifteenth largest in the sample, with twenty-five cases. All cases (7 or 28%) in cluster 79 were in this class (type "B"). Class 9a was also represented in five type "C" clusters: clusters 75-78, and 80. Each had 2-4 cases, and except for 75 and 80, was entirely devoted to this class. It seems that because of the silent period in the middle of many of these sounds, variations in duration had still more drastic effects on cluster analysis. Cluster 77 was very short (mean of 0.33 sec), clusters 75, 79 and 80 had their mean duration in the 0.46-0.57 sec range, while clusters 76 and 78 had mean durations of 0.62 and 0.78 sec, respectively. There were some differences in bandwidth between clusters. Clusters 75 and 76 had relatively narrow bandwidth (2.77 and 2.88 kHz), clusters 78-80 had bandwidth relatively close to the class average (3.82, 3.20 and 4.12 kHz, respectively). Only cluster 77 had a very broad bandwidth: 7.06 kHz. The sound in cluster 75 also differed in having a subunit in the middle (Figure 42). The rest of the class came from three type "F" clusters: one case in cluster 51, and three in each of clusters 61 and 83.

GROUP 10.

These sounds were long (means varied from 1.04-3.32 sec, Table 17) series of broadband clicks (except for class 10c, mean bandwidth was in the 3.39-4.88 kHz range). Repetition rate was slow, each click being well separated both on the spectrograms and to the human ear. Mean peak frequencies were in the 0.9-1.5 kHz region for all classes. Group 10 was divided into three classes.

Table 17. Characteristics and clustering of the three classes in Group 10.

For each class, the number of cases (n), mean dominant frequency at three points (start, middle, and end of sound), minimum and maximum frequencies, and duration are given, with the standard deviation in brackets. Structure of the sounds and the number of clusters of each type are also shown. The highest proportion (%) of the class found in a single cluster is in brackets, below the appropriate cluster type.

CLASS (n)	DOMINANT FREQ (kHz) START	MIDDLE	END	MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)	STRUCTURE *	CLUSTER TYPE ** A	B	C	D	E	F
10a	1.27	0.97	1.38	0.19	5.07	1.88	SN		1	2			8
(36)	(0.77)	(0.36)	(1.01)	(0.13)	(2.27)	(1.58)			(28)				
10b	1.35	1.51	1.16	0.40	3.78	1.04	SN			6			9
(28)	(0.46)	(0.79)	(0.40)	(0.24)	(1.41)	(0.91)							(14.3)
10c	1.18	1.35	0.92	0.24	2.13	3.32	S	1					
(1)	-	-	-	-	-	-		(100)					

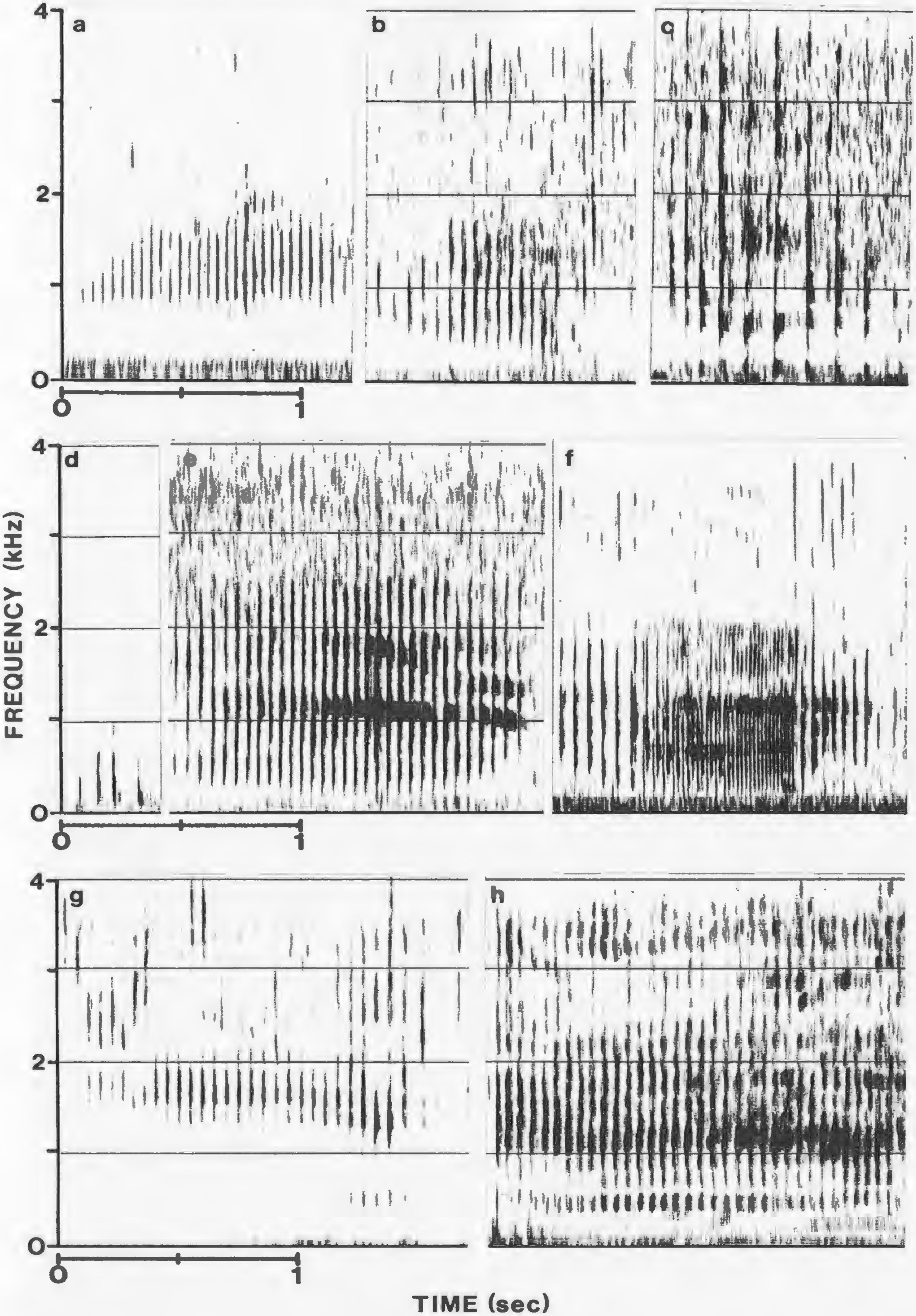
* Structure types are as in Table 6, p. 64.
** Cluster types are described in Table 5, p. 62.

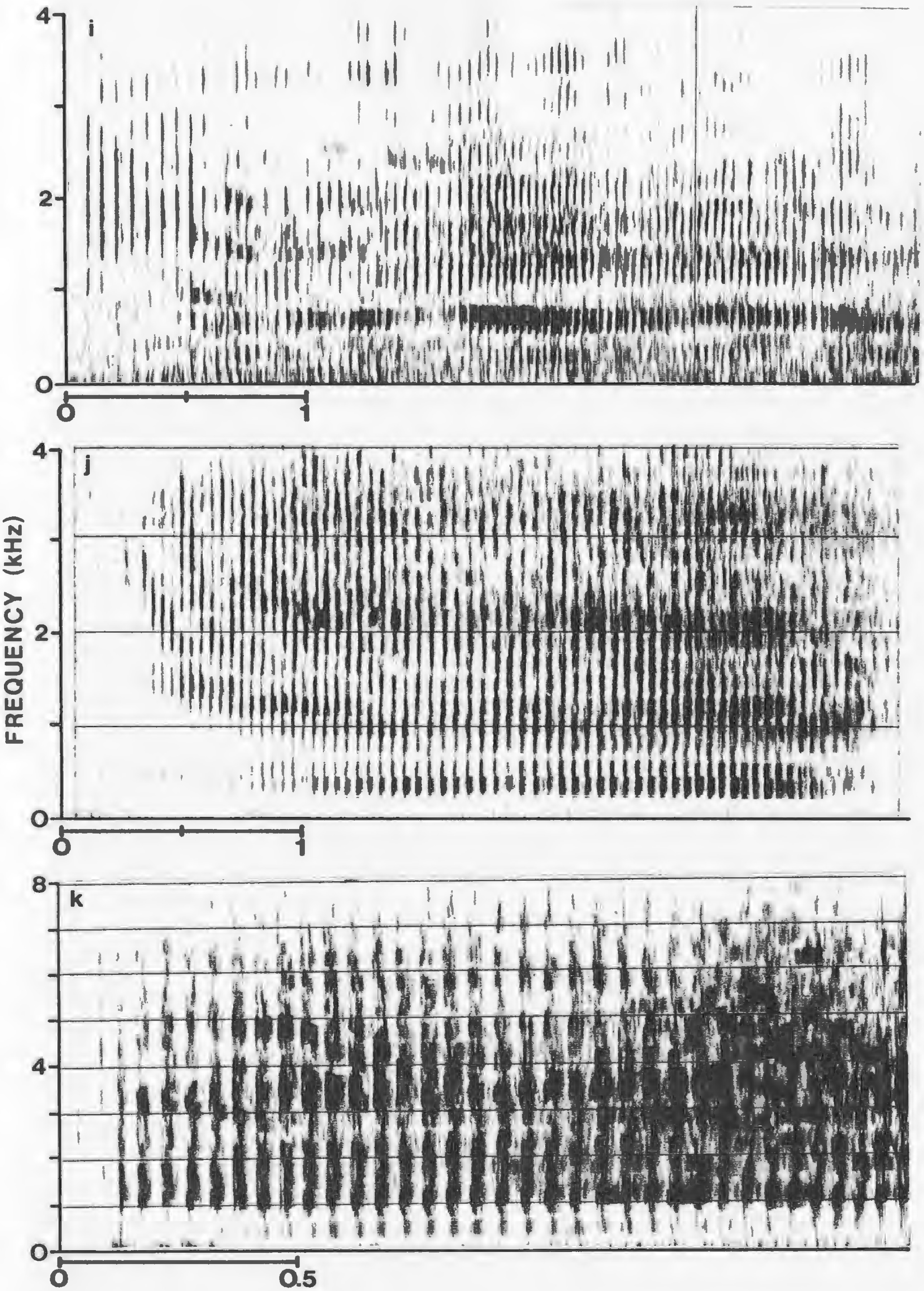
Class 10a. These pulsive sounds had a slow repetition rate and a long duration (mean of 1.88 sec, Table 17) (Figure 43). Repetition rate was constant except for one case, where it was faster in the middle section of the sound (Figure 43f). The subunits were broadband clicks, with bands of higher intensity, generally in the 0.5-2.0 kHz region. Bandwidth averaged 4.88 kHz: mean minimum frequency was 0.19 kHz, while maximum frequency averaged 5.07 kHz, but was very variable. Most sounds had little energy below 0.3 kHz, which was important in differentiating them from class 8a (Figure 36). Peak frequency averaged 1.27 kHz at the beginning, 0.97 at the middle, and 1.38 at the end. Peak frequency was relatively constant over the duration of the sounds, although frequency modulation of as much as 1 kHz was found in some of the longest cases.

Figure 6b in Beamish (1979) corresponds to this class, although it is a case of relatively narrow bandwidth.

With thirty-six members, class 10a ranked ninth in size. Ten (28%) of them came from cluster 86, accounting for 71% of the cluster (type "B"). Two clusters, 84 and 85, were of type "C" relative to this class: cluster 84 had five elements, three of which being of class 10a, while cluster 85 had only one element. Eight type "F" clusters also contained 1-7 sounds of this type: 6, 58, 61, 70, 82, 83, 87 and 98. Duration, bandwidth and minimum frequency were very variable. Duration was less than 1 sec in clusters 58, 61, 83, and 84, 1-2 sec in clusters 6, 82, 85 and 98, and over 2 sec in the other clusters. Bandwidth was less than 2 kHz in clusters 58, 2-4 kHz in clusters 61, 70, 83, 84, 85 and 98, while it was over 4 kHz in clusters 6, 82, 86 and 87. Clusters 58, 61, 70 and 82-84 had mean minimum frequencies below 0.2 kHz, while it was 0.2-0.4

Figure 43. Some spectrograms of class 10a sounds. a is from cluster 98; b is from 84; c is from 83; d is from 57; e-f are from 82; g is from 6; h, j and k are from 86; and i is from 70. i and k are not complete. k is the same sound as h. Analysis filter and breaks in the abscissa are as in Figure 6, p. 67.


a
b
c
d
e
f
g
h
4
2
0
0
1
FREQUENCY (kHz)
TIME (sec)

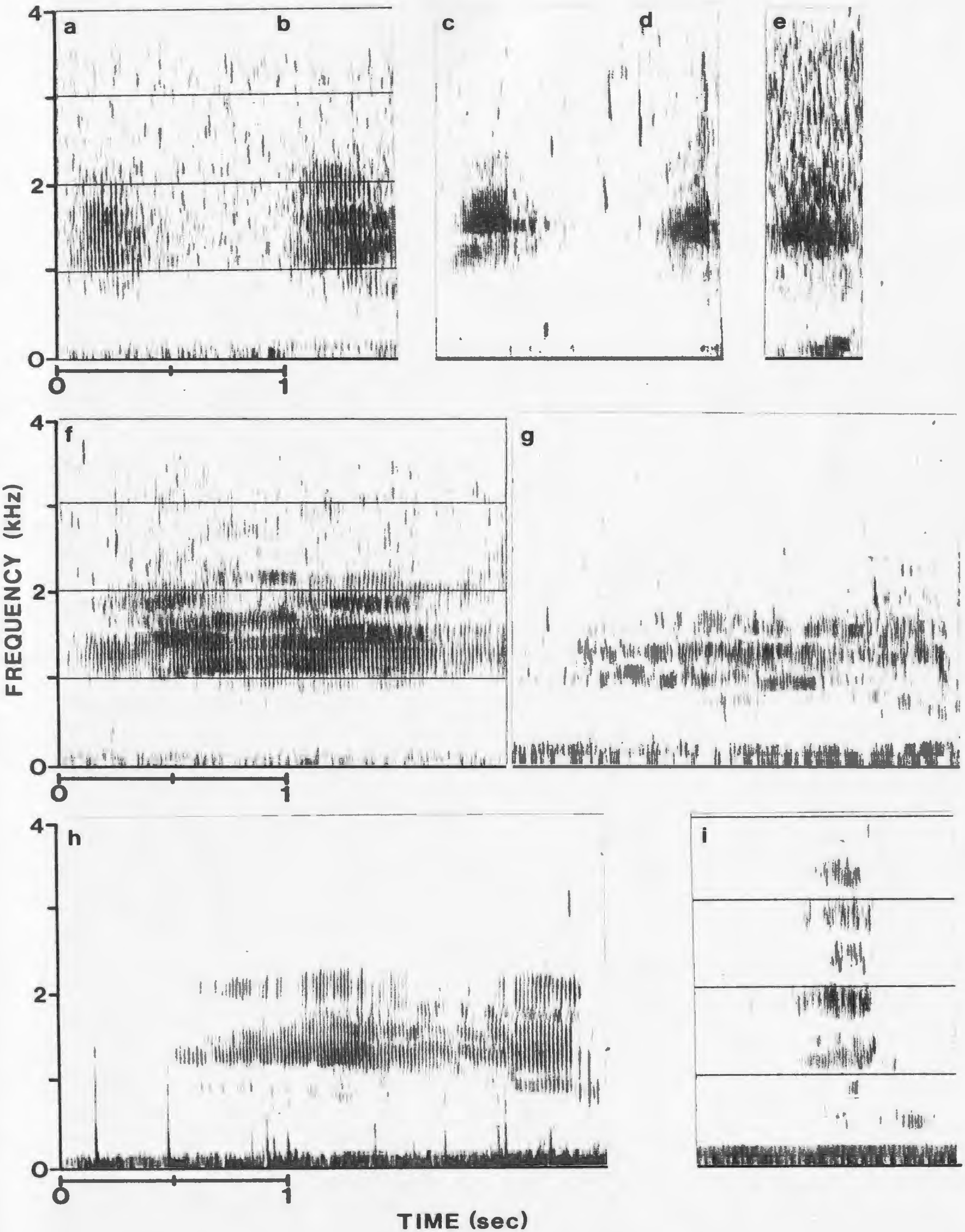

i
j
k
FREQUENCY (kHz)
4
2
0
8
0.5

kHz for clusters 85, and 86, and over 4 kHz for clusters 6, 47 and 54 (Appendix D). These sounds had very similar acoustic properties however, and were fused for this reason.

Class 10b. These sounds were also long (mean of 1.04 sec, Table 17) click trains (e.g., pulsive sounds with distinct subunits with a 150 Hz analysis filter). Like the previous class, duration was very variable. Mean minimum frequency was higher (0.40 kHz) however, and mean maximum frequency lower (3.78 kHz) than in the previous class, resulting in a narrower bandwidth (3.39 kHz). Most of the energy was in the 1-2 kHz range. Peak frequency averaged 1.35 kHz at the beginning, 1.51 at the middle, and 1.16 at the end. Pulse rate was also faster than in class 10a (Figure 44). It must be emphasized that this was a qualitative criterion, since pulse rate was not measured. However, the aural impression was very different.

Class 10b was the thirteenth largest in the data set, with 28 cases. It was split in many clusters, six of which being of type "C". Clusters 68, 89 and 91 were single-element clusters. Cluster 87 had four cases, three of which were from class 10b. Clusters 88 and 90 each had one of their two elements in this class. The other members were scattered in nine type "F" clusters: 47, 50, 54, 61, 67, 81-82, 84 and 98. Mean duration was shorter than the class average in clusters 47, 50, 54, 61, 67, 81, 88 and 90; longer in clusters 82, 87 and 98; and about the class average in the others. Mean bandwidth was narrow in clusters 47, 61, 67 and 89; it was broader than the class average in clusters 47, 50, 61, 67-68, 81-82, 87-88. Clusters 54, 61, 67-68, 82 and 84 had low frequencies (mean minimum frequency of 0.18 kHz), while clusters 47, 81, 88, 90 and 98 had mean minimum frequencies above 0.52

Figure 44. Some spectrograms of class 10b sounds. a-c are from cluster 50; d-e are from 54; f and h are from 87; g is from 98; i is from 90. Analysis filter and breaks in the abscissa are as in Figure 6, p. 67.


4
2
0
a
b
c
d
e
0
1
4
2
0
f
g
0
1
4
2
0
h
i
0
1
FREQUENCY (kHz)
TIME (sec)

kHz (Appendix D).

Class 10c. There was only one case in this class. It was similar to class 10b, being pulsive with a slow repetition rate, and having most of its energy between 0.8 and 1.5 kHz (Figure 45). However, repetition rate was slower, like in class 10a, while the subunits had a narrow bandwidth and longer duration (Figure 45). Duration of the sound was 3.32 sec.and bandwidth 1.89 kHz, with a minimum and maximum frequency of 0.24 and 2.13 kHz respectively (Table 17). Peak frequency measurements were 1.18, 1.35 and 0.92 kHz. Cluster analysis recognized this sound as different, since it was the only case found in cluster 92 (type "A").

GROUP 11.

Two classes were found in group 11, both with only one case each. They were long, with broad bandwidth and a complex structure (Table 18). One class was definitively pulsive, although pulse rate was variable. It was not clearly pulsive in the other class.

Class 11a. Class 11a had only one case. Its structure was complex: most of the sound's energy was in 2 bands (0.5-1.5 and 2-3 kHz), there was frequency and amplitude modulation, noise was present, and at least parts of the sound were pulsive (Figure 46). Duration was 1.83 sec, minimum frequency 0.13 kHz, and maximum frequency 7.29 kHz, for a bandwidth of 7.16 kHz (Table 18). Peak frequency varied from 2.56 kHz at the beginning, to 1.21 in the middle and 0.69 at the end. This sound was found in cluster 86, accounting for only 7% of the cluster.

Class 11b. Again, this class was found only once in the data set. It was a combination of an irregular click train with a faint blow. The bandwidth of the individual clicks increased from the beginning to the

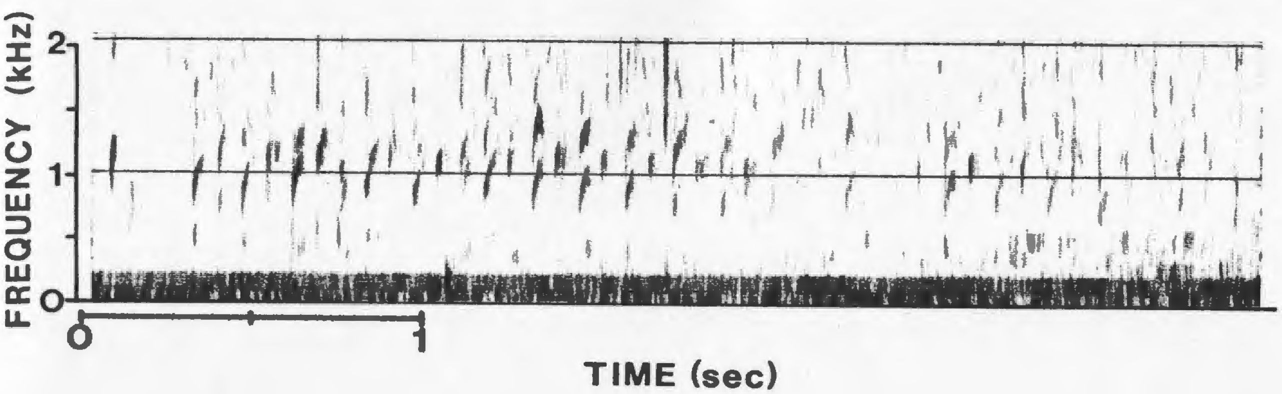


Figure 45. Spectrogram of class 10c sound, found in cluster 92. Analysis filter is as in Figure 6, p. 67.

Table 18. Characteristics and clustering of the two classes in group 11.

For each class, the number of cases (n), mean dominant frequency at three points (start, middle, and end of sound), minimum and maximum frequencies, and duration are given, with the standard deviation in brackets. Structure of the sounds and the number of clusters of each type are also shown. The highest proportion (%) of the class found in a single cluster is in brackets, below the appropriate cluster type.

CLASS (n)	DOMINANT FREQ (kHz)			MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)	STRUCTURE *	CLUSTER TYPE **					
	START	MIDDLE	END					A	B	C	D	E	F
11a	2.56	1.21	0.69	0.13	7.29	1.83	FN					1	
(1)	-	-	-	-	-	-						(100)	
11b	0.34	0.61	1.45	0.13	4.08	3.52	SN					1	
(1)	-	-	-	-	-	-						(100)	

* Structure types are as in Table 6, p. 64.
** Cluster types are described in Table 5, p. 62.

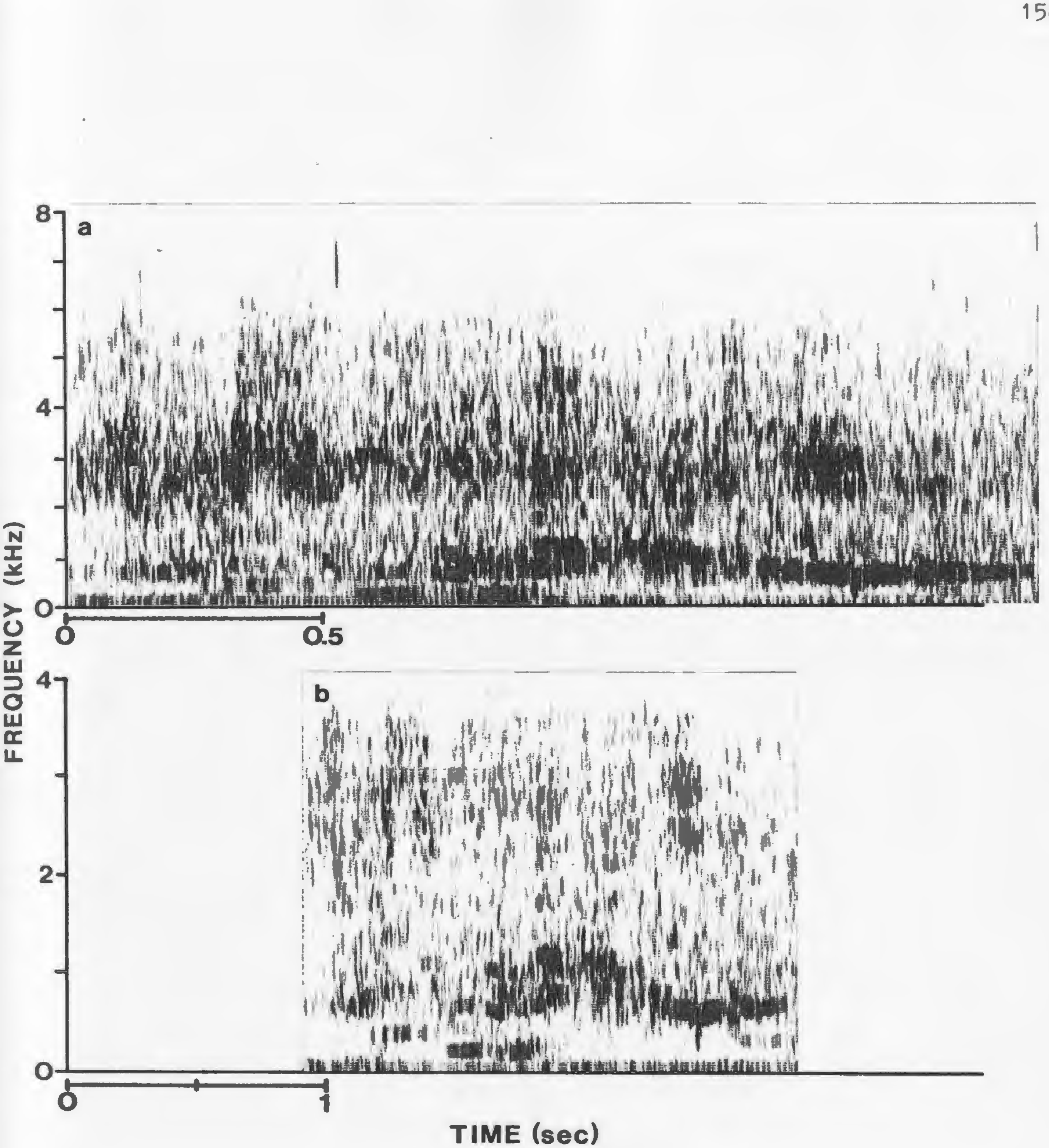


Figure 47. Spectrograms of class 11a sound, found in cluster 86. Analysis filter is as in Figure 6, p. 67.

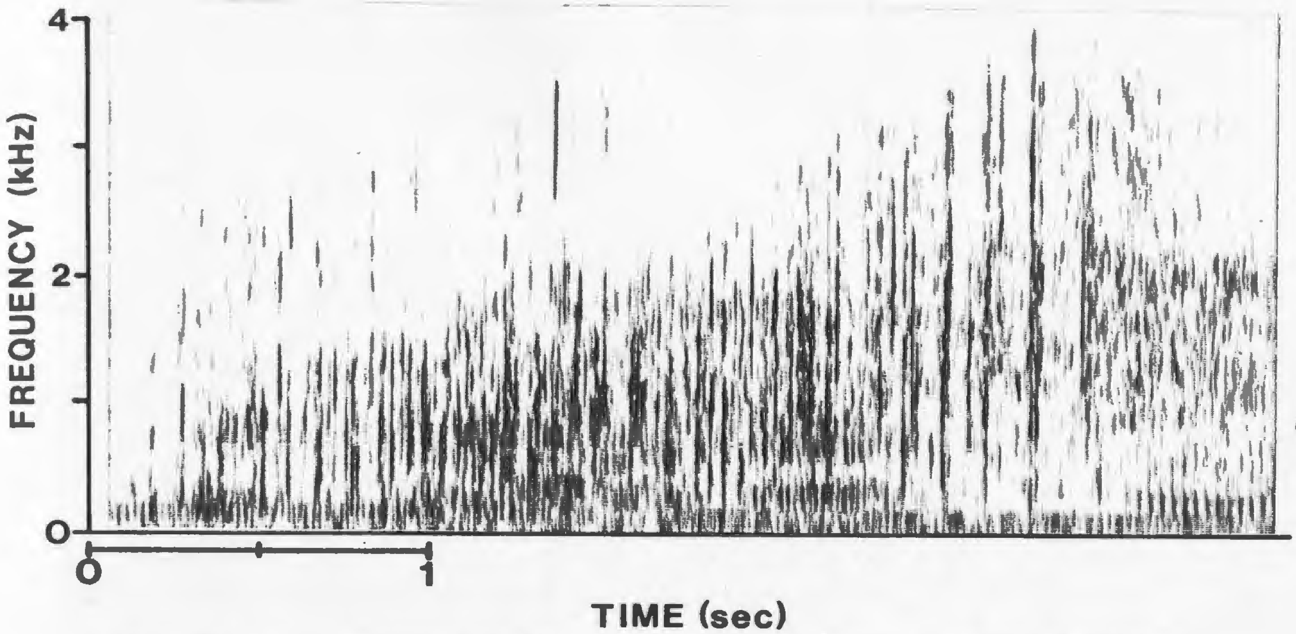


Figure 47. Spectrogram of class 11b sound, from cluster 70. Analysis filter is as in Figure 6, p. 67.

Table 19. Characteristics and clustering of the three classes in group 12.

For each class, the number of cases (n), mean dominant frequency at three points (start, middle, and end of sound), minimum and maximum frequencies, and duration are given, with the standard deviation in brackets. Structure of the sounds and the number of clusters of each type are also shown. The highest proportion (%) of the class found in a single cluster is in brackets, below the appropriate cluster type.

CLASS (n)	DOMINANT FREQ (kHz)			MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)	STRUCTURE *	CLUSTER TYPE **					
	START	MIDDLE	END					A	B	C	D	E	F
12a (22)	1.31 (0.62)	1.20 (0.77)	1.12 (0.72)	0.32 (0.21)	4.94 (1.88)	1.80 (1.05)	F			8 (23)			3
12b (2)	0.85 (0.70)	0.27 (0.05)	0.20 (0.01)	0.13 (0.00)	2.99 (1.44)	1.30 (0.51)	F	1 (50)					1 (50)
12c (8)	1.82 (1.09)	2.05 (0.84)	2.90 (0.80)	0.16 (0.05)	6.70 (0.90)	2.10 (1.24)	F	1 (50)		2			

* Structure types are as in Table 6, p. 64.
** Cluster types are described in Table 5, p. 62.

end, but was always fairly broad (Figure 47). Minimum and maximum frequencies were 0.13 and 4.08 kHz respectively, for a bandwidth of 3.95 kHz (Table 18). It was long (3.52 sec), and peak frequency increased from 0.34 kHz at the beginning to 1.45 to the end, passing by 0.61 kHz at the middle. It was not recognized by cluster analysis: it was found in cluster 70, which contained mostly sounds from classes 8b, 8c and 8e. However, it sounded very different.

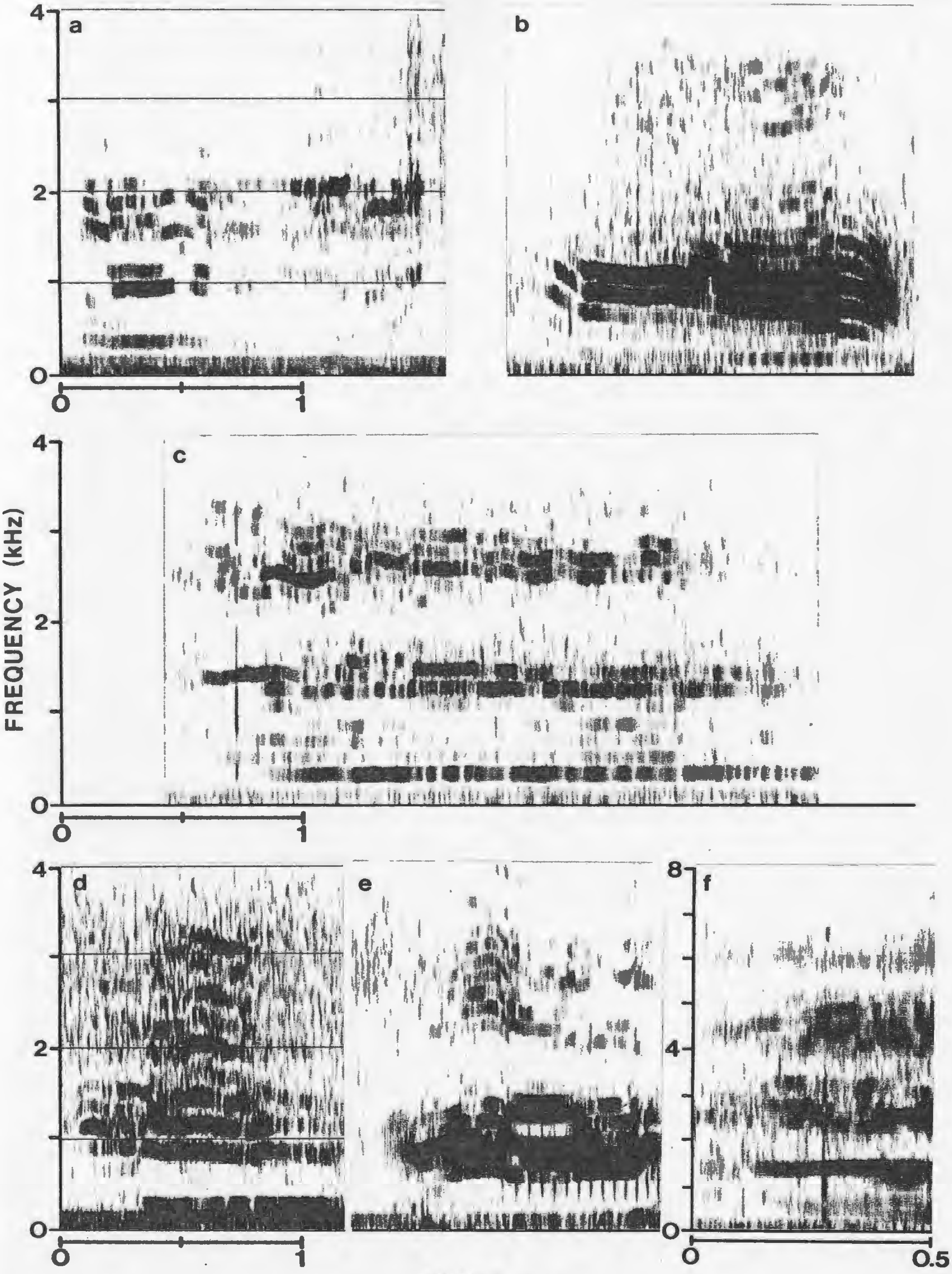
GROUP 12.

These sounds were pulsive, and their fast repetition rate resulted in a complex harmonic structure with an analysis filter of 150 Hz. Group 12 was divided in three classes, mainly on the account of their different bandwidth and peak frequencies (Table 19). All were long and had relatively broad bandwidths.

Class 12a. These sounds were very long (mean of 1.8 sec, Table 19) and had a wide frequency range (4.62 kHz), a high pulse rate (individual components were rarely visible) and most of their energy between 1 and 2 kHz. Hence, peak frequency measurements were 1.31, 1.20 and 1.12 kHz. Within these limits, there was much variability (between and within sounds) in sound intensity, peak frequency, repetition rate, bandwidth and duration (Figure 48). Minimum and maximum frequencies averaged 0.32 and 4.94 kHz. Usually, there was little energy below 0.5 kHz.

Class 12a was the sixteenth largest of the sample, with 22 cases. These sounds were usually kept apart from the other classes by cluster analysis. However, the class was split in eight type "C" clusters. Cluster 98 had five of them (23%), which was only 50% of the cluster's

Figure 48. Some spectrograms of class 12a sounds. a is from cluster 98; b and d are from 82; c and f are the same sound, from cluster 86 (f is incomplete); e is from 95. Some clicks from another sound can be seen in the last half of e. Analysis filter and breaks in the abscissa are as in Figure 6, p. 67.



a
b
c
d
e
f
FREQUENCY (kHz)
TIME (sec)
0
1
2
4
8
0.5

10 elements. Clusters 93-97 did not contain any other class, but only cluster 93 had more than one case (n=3). Clusters 71 and 90 had two elements each, and for both, one was from class 12a. The other cases came from type "F" clusters 70, 82 and 86. In cluster 94, duration was much shorter than average (0.41 sec); it was 1-2 sec in clusters 82, 90, 95 and 98, and longer than than 2 sec for the other clusters (Appendix D). Cluster 98 had the narrowest bandwidth (2.65 kHz), while clusters 86, 93, 95 and 97 had bandwidth of 6 kHz or more. The other clusters had bandwidth in the 3-5 kHz range. Clusters 90, 94 and 98 had mean minimum frequencies of 0.35 kHz or higher, while it was in the 0.2-0.3 kHz range for clusters 86, 95 and 96, and below 0.2 kHz for the other clusters.

Class 12b. These sounds were pulsive with a fast repetition rate. They differed from those of the previous class by their frequency downsweep: peak frequency averaged 0.85 kHz at the beginning, 0.27 at the middle, and only 0.2 at the end (Table 19). Also, they had little energy above 1 kHz (Figure 49). The fast pulse rate resulted in many harmonics, which was reflected in the broad bandwidth (2.86 kHz). Amplitude modulation (other than the pulse rate) was also present. Minimum and maximum frequencies averaged 0.12 and 2.99 kHz respectively. Mean duration was 1.3 sec.

There were only two cases in this class, which ranked thirty-seventh overall in size. The shorter one came from a small cluster of two sounds, 99, which had a mean duration of 0.72 sec (Appendix D). The other was found in cluster 82, where it accounted for only 5% of the cluster. Cluster 82 contained many classes, including four from class 12a and seven from class 10a. They were very similar once digitized,

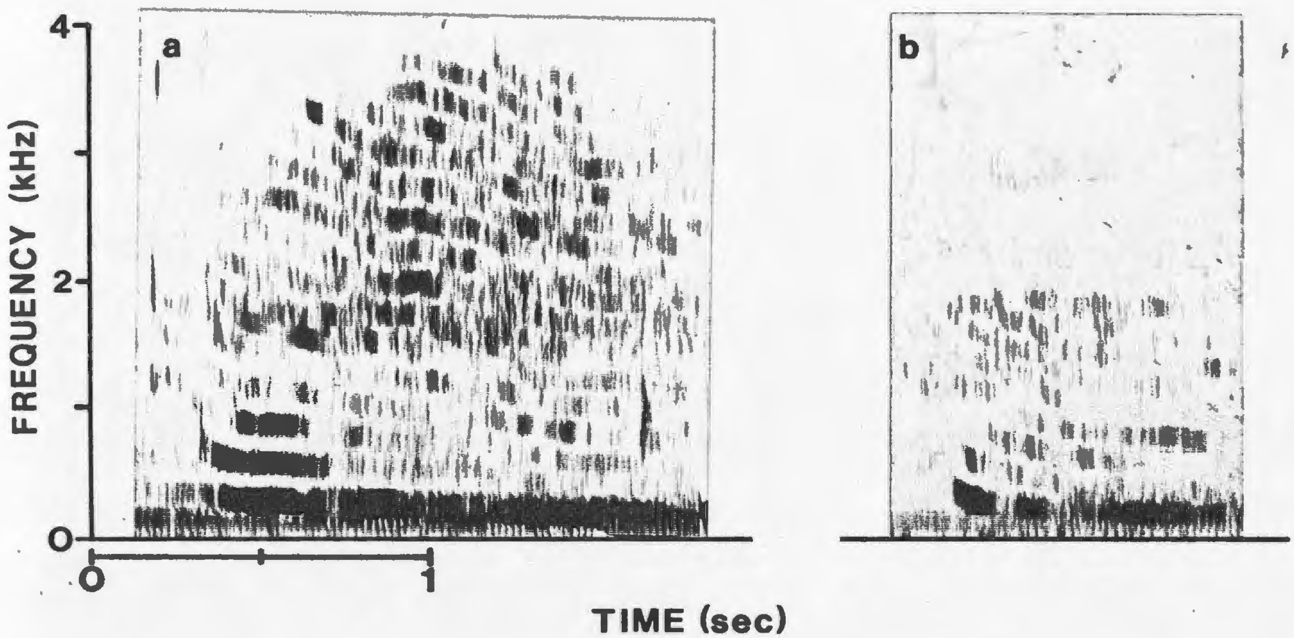


Figure 49. Spectrograms of class 12b sounds. a is from cluster 82; b is from 99. Analysis filter and break in the abscissa are as in Figure 6, p. 67.

since frequency modulation was only coarsely coded and pulse rate not coded.

Class 12c. These sounds were similar to those of class 12a: they were long (mean duration of 2.10 sec, Table 19), pulsive with a high repetition rate, while frequency and amplitude modulation were highly variable (Figure 50). But here most of the energy was in the 2-4 kHz band: peak frequency measurements averaged 1.82, 2.05 and 2.9 kHz at the three sampling points. Except for one case, there was very little energy below 1.5 kHz. Mean minimum and maximum frequencies were 0.16 and 6.7 kHz respectively, for a mean bandwidth of 6.54 kHz.

With eight cases, class 12c ranked twenty-third in size. Cluster analysis isolated it from the other sound types, but split the class in three clusters. Cluster 100 had half of the class (4 cases). Two cases were found in each of clusters 101 and 102. These three clusters contained only sounds from class 12c. Mean bandwidth was over 6 kHz for the three clusters (Appendix D), but the average duration was 2.88 sec in cluster 100, 1.11 sec in cluster 101 and 1.54 sec in cluster 102. There was also less energy below 2 kHz in the last 2 clusters.

GROUP 13.

The three classes forming group 13 were pulsive (although a few cases were tonal) and characterized by a frequency downsweep. When pulsive, they had a very fast repetition rate. Peak frequency was very variable, both between and within classes (Table 20). Except for class 13b, there was little energy below 1 kHz. These classes were shorter than those of the previous group: classes 13a and 13c had less than 0.3 sec of mean duration, while the other class lasted less than half a

Figure 50. Some spectrograms of class 12c sounds. a and d are from cluster 100. b-c and e are from cluster 101. b and c are the same sound. Analysis filter and breaks in the abscissa are as in Figure 6, p. 67.

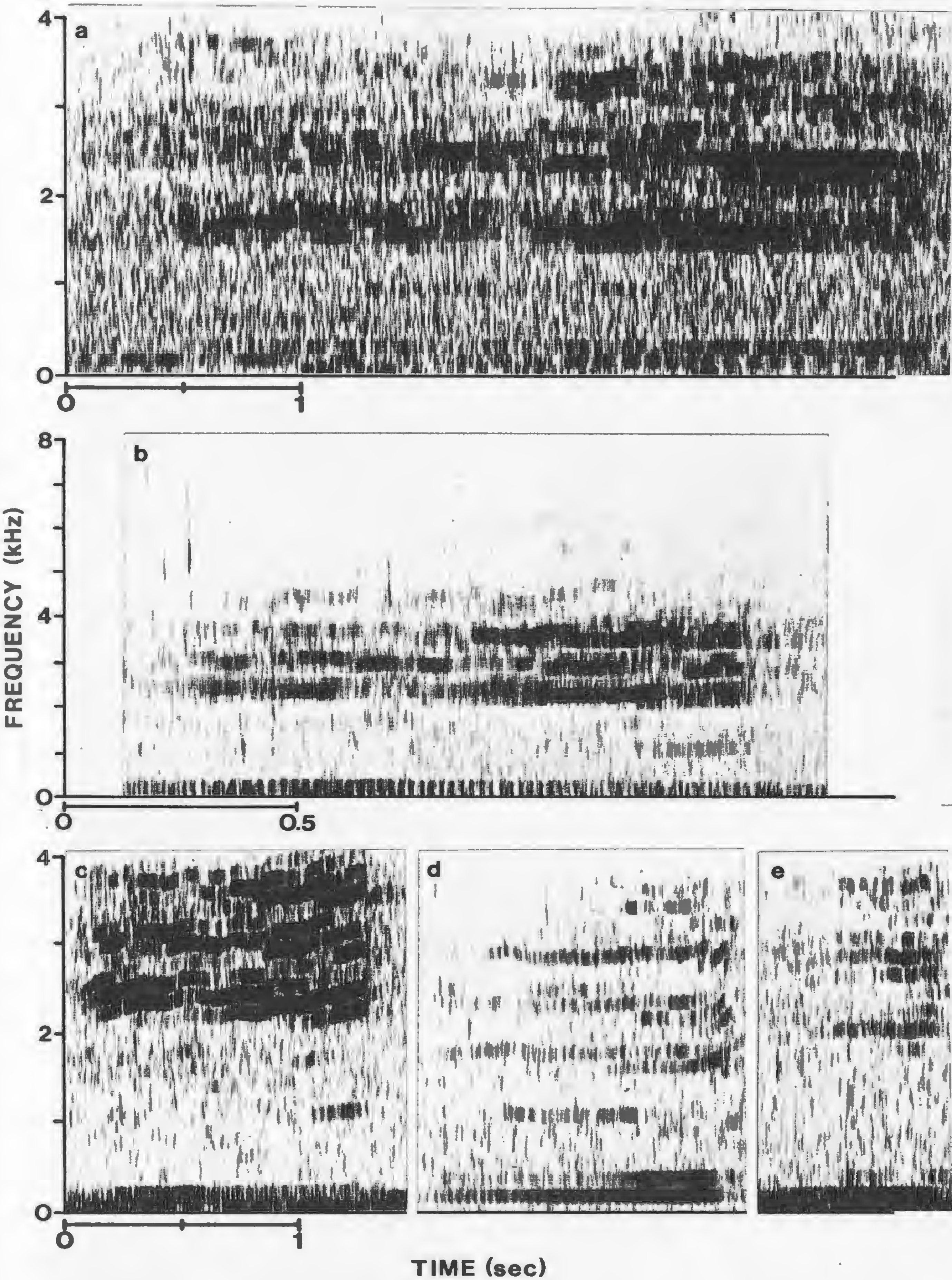

a
b
c
d
e
FREQUENCY (kHz)
TIME (sec)
4
2
0
8
4
0
0.5
1

Table 20. Characteristics and clustering of the three classes in Group 13.

For each class, the number of cases (n), mean dominant frequency at three points (start, middle, and end of sound), minimum and maximum frequencies, and duration are given, with the standard deviation in brackets. Structure of the sounds and the number of clusters of each type are also shown. The highest proportion (%) of the class found in a single cluster is in brackets, below the appropriate cluster type.

CLASS (n)	DOMINANT FREQ (kHz) START	MIDDLE	END	MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)	STRUCTURE *	CLUSTER TYPE ** A	B	C	D	E	F
13a	2.40	2.24	2.27	0.72	5.76	0.28	(FT)		1	6			7
(33)	(1.17)	(1.28)	(1.11)	(0.38)	(1.90)	(0.23)			(49)				
13b	1.22	0.78	0.61	0.25	3.82	0.42	(FNS)			5			12
(26)	(0.93)	(0.56)	(0.27)	(0.11)	(2.30)	(0.21)							(15)
13c	6.65	3.79	7.13	3.34	8.15	0.15	FN					1	
(1)	-	-	-	-	-	-						(100)	

* Structure types are as in Table 6, p. 64.
** Cluster types are described in Table 5, p. 62.

second in average.

Class 13a. Most of these sounds were pulsive with a decreasing repetition rate, which was seen as a reduction in the distance between harmonics on the spectrograms (Figure 51). Some cases were tonal with 1-9 harmonics. All but a few cases were characterized by a frequency downsweep. For the others, peak frequency remained about constant, or the frequency downsweep was preceded or followed by a fainter upsweep (resulting in a up-down or down-up structure). Maximum intensity would frequently shift from one harmonic to another, masking partially the frequency downsweep from the measurements of peak frequency, which averaged 2.40 kHz at the beginning, 2.24 at the middle, and 2.27 at the end (Table 20). There was little energy below 1 kHz (mean minimum frequency of 0.72 kHz). The many harmonics resulted in a broad bandwidth (5.04 kHz) and a mean maximum frequency reaching 5.76 kHz. These sounds lasted an average of 0.28 sec.

Class 13a had 33 cases and was the eleventh largest in the repertoire. Cluster 103, type "B", had 16 of them (49% of the class, and 73% of the cluster). There were also six type "C" clusters. Clusters 104-107 had only one case each, while clusters 88 and 114 had two cases each, one of them belonging to class 13a. Four of these clusters (103-106) had short mean durations (0.15-0.21 sec) (Appendix D). Duration was around 0.3 sec in clusters 88 and 114, and 0.67 sec in clusters 107. Clusters 88 and 105 had a mean bandwidth of less than 4.65 kHz (the class average), while all the other clusters had mean bandwidth in the 5.24-7.57 kHz range. Cluster 103 had a high mean minimum frequency (1.05 kHz), while cluster 106 had a mean minimum frequency of 0.13 kHz. It was in the 0.36-0.83 kHz range for the other clusters. Also, the

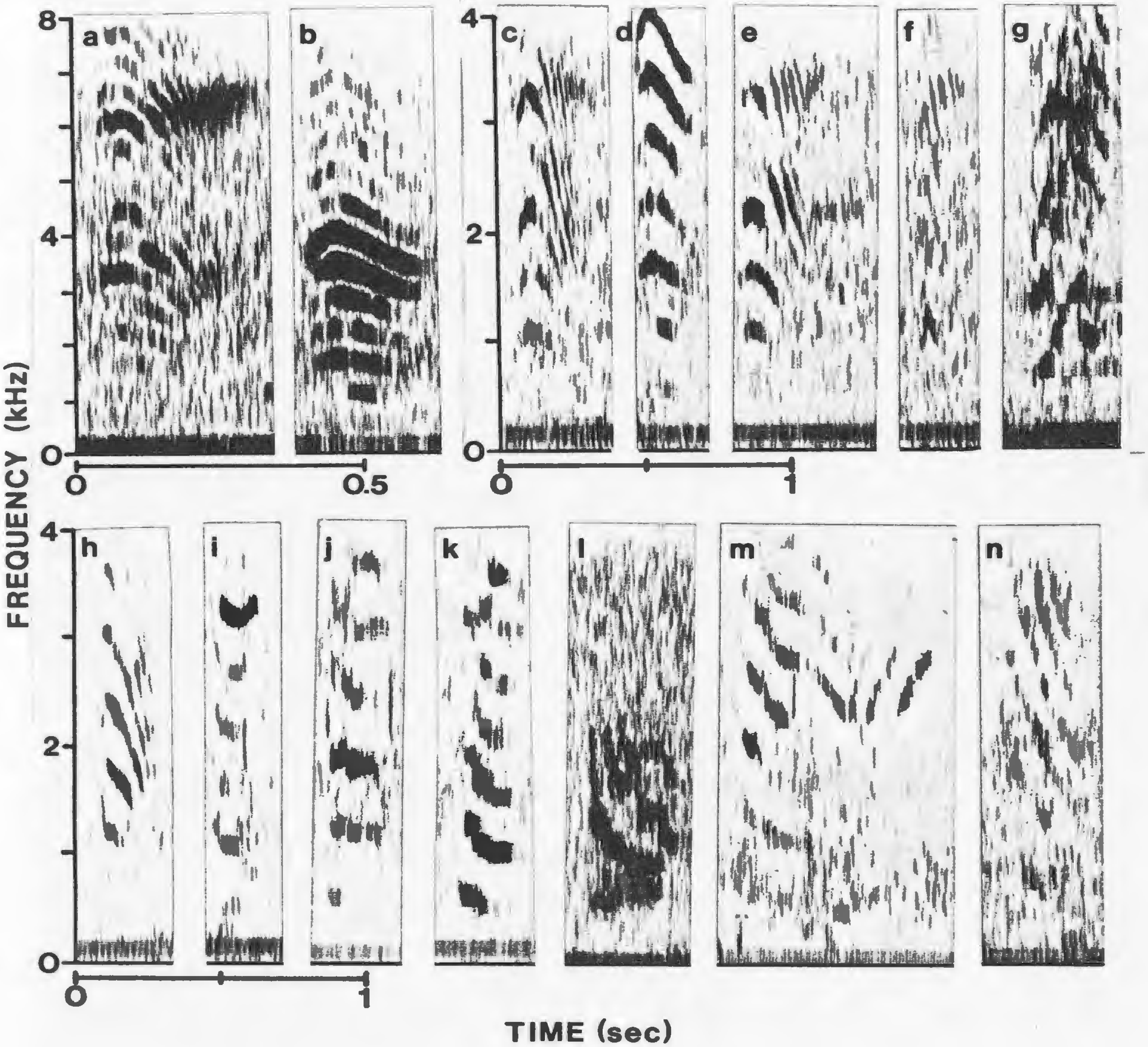


Figure 51. Some spectrograms of class 13a sounds. a and c as well as b and d are pairs of the same sound. a-h are from cluster 103; i is from 104; j from 41; k from 105; l from 49; m from 107; n from 114. Analysis filter and breaks in the abscissa are as in Figure 6, p. 67.

sound in cluster 107 had two inflection points (up-down-up), while the sounds in clusters 88 and 104 had a fairly constant peak frequency. A few other cases were found in seven type "F" clusters: 2, 6, 41, 49, 51, 52 and 109. Many of these clusters had durations of 0.22 sec or less (41, 49, 51), narrower bandwidth than average (2, 41, 51, 109) and/or had components in low frequencies (51, 52, 109). One cluster (6) was broadband and very long (mean duration of 1.52 sec).

<u>Class 13b.</u> These sounds were pulsive, with a fairly high repetition rate. A short frequency increase was sometimes present at the beginning, but most of the sound consisted in a slow frequency downsweep coupled with a decrease in repetition rate. On some of them, the repetition rate became slow enough to discriminate the subunits toward the end of the sound (Figure 52). Again, some cases were tonal. High frequencies were sometimes present, making a few of these sounds similar to some cases of the previous class. They differed from class 13a in having their dominant frequency below 1 kHz, less harmonics, and often a slower frequency downsweep and decrease in repetition rate. Class 13b sounds were also longer (0.42 sec, Table 20). Peak frequency measurements averaged 1.22, 0.78 and 0.61 kHz. Mean minimum and maximum frequencies were 0.25 and 3.82 kHz, for a mean bandwidth of 3.57 kHz.

Class 13b had 26 members and was the fourteenth largest in the data set. It was not very well recognized by cluster analysis. Three type "C" clusters (110-112) were entirely made of this type of sounds, but were very small (n=1,1 and 2 respectively). Clusters 64 and 109 were also of type "C" and each had one of their two cases in class 13b. Mean minimum frequency was above 0.16 kHz in these five clusters. Cluster 112 also had a very broad frequency range (7.4 kHz), while clusters

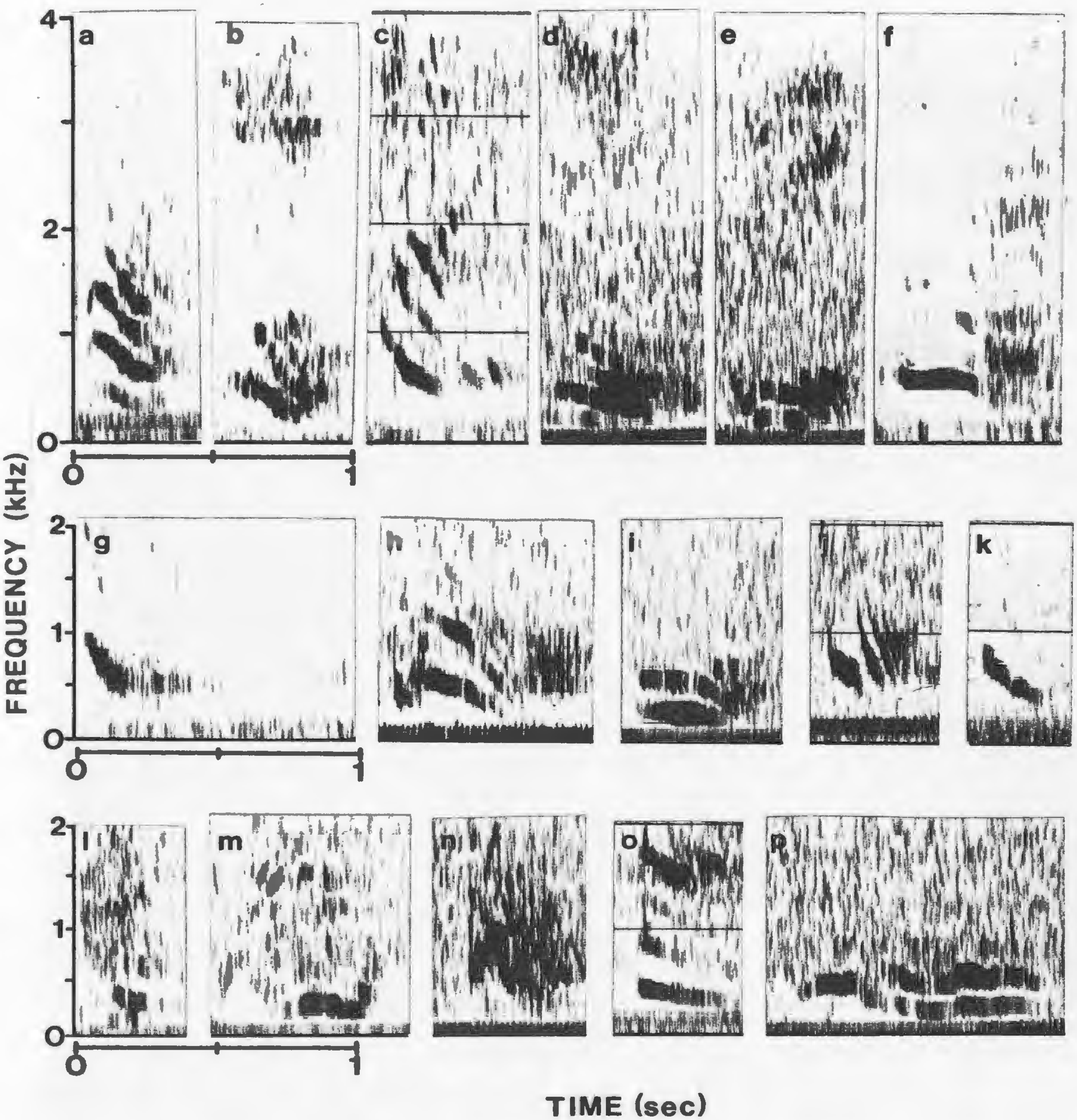


Figure 52. Some spectrograms of class 13b sounds. a-b are from cluster 112; c is from 108; d from 109; e from 66; f from 2; g from 110; h from 111; i from 40; j from 55; k from 61; l from 54; m-n from 61; o from 64; p from 80. Analysis filter and breaks in the abscissa are as in Figure 6, p. 67.

110-111 lasted 0.78 and 0.92 sec respectively (Appendix D). However, cluster 61 contained the highest number of these sounds (4 or 15% of the class, but only 2% of the cluster) and was of type "F". The other cases were found in eleven other type "F" clusters: 2, 14, 40, 51, 54-57, 61, 66, 80 and 109. Clusters 57, 61, 66 and 80 had components of very low frequencies (mean minimum frequencies of 0.15 kHz or less), while clusters 2, 40, 51, 54-57, and 109 were relatively short, with mean durations of 0.08-0.32 sec.

Class 13c. This class had only one case. It was a pulsive high frequency sound found in cluster 103. It had a frequency contour similar to those of class 13a sounds, but sounded very different (Figure 53). The repetition rate was slow enough to distinguish the individual components with an analysis filter of 300 Hz (Table 20). It was short (0.15 sec) and broadband (from 3.34 kHz up past the limit of 8 kHz). Peak energy was lower at the middle (3.79 kHz) than at the beginning (6.65 kHz) or the end (7.13 kHz).

PROBABILITY OF OCCURRENCE OF EACH SIGNAL

As can be seen in Table 21, there was a great deal of variation in probability of occurrence of each class in the data set. Class 7d, the most frequently found in this sample, was used 194 times while as many as 12 classes were used only once. The five largest classes represented 53.1% of the data set. Even if only seven classes were used more than 50 times, twenty-two classes were found at least ten times in the sample. These relatively well used classes represented 93.6% of the 1255 cases, the rest being split in twenty-eight small classes.

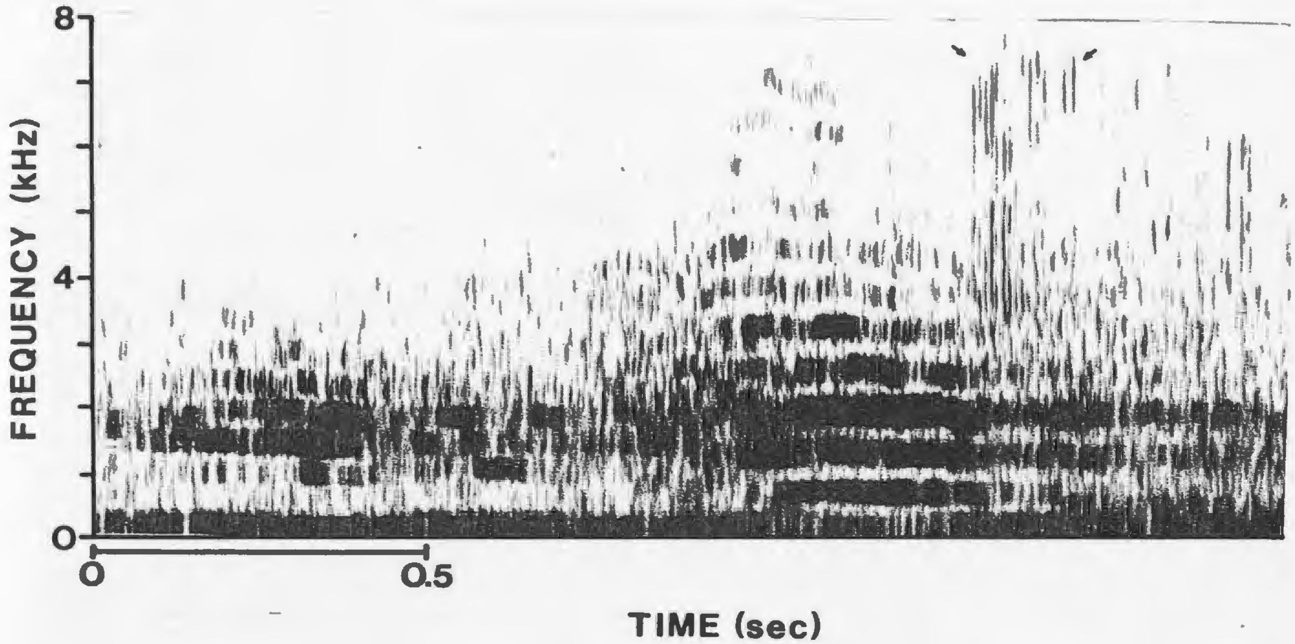


Figure 53. Spectrogram of class 13c sound, from cluster 103. Two sounds can be seen on this spectrogram. Sound 13c is in the upper right portion, between the two arrows. The other sound, mostly below 3 kHz, is from class 2f. Analysis filter is as in Figure 6, p. 67.

Table 21. Rank, size and frequency of each of the 50 classes in the sample of humpback sounds.

RANK *	CLASS	SIZE	FREQ	CUM. FREQ
1	7d	194	15.4	15.4
2	3c	139	11.1	26.5
3	5b	134	10.7	37.2
4	1a	100	8.0	45.2
5	7c	99	7.9	53.1
6	4a	64	5.1	58.2
7	7a	57	4.5	62.7
8	8a	49	3.9	66.6
9	10a	36	2.9	69.5
10	1b	34	2.7	72.2
11	13a	33	2.6	74.8
12	3d	29	2.3	77.1
13	10b	28	2.2	79.3
14	13b	26	2.1	81.4
15	9a	25	2.0	83.4
16	12a	22	1.8	85.2
17	5a	21	1.7	86.9
18(17)	8b	21	1.7	88.6
19	3b	19	1.5	90.1
20	7e	17	1.3	91.4
21	2f	15	1.2	92.6
22	2g	12	1.0	93.6
23	4b	8	0.6	94.2
24(23)	12c	8	0.6	92.8
25	8e	7	0.5	95.3
26	8c	5	0.4	95.7
27(26)	8d	5	0.4	96.1
28	2b	4	0.3	96.4
29(28)	2e	4	0.3	96.7
30(28)	2h	4	0.3	97.0
31(28)	2i	4	0.3	97.3
32(28)	8f	4	0.3	97.6
33	2a	3	0.2	97.8
34(33)	2d	3	0.2	98.0
35(33)	5c	3	0.2	98.2
36(33)	7f	3	0.2	98.4
37	6a	2	0.2	98.6
38(37)	12b	2	0.2	98.8
39	1c	1	0.1	98.9
40(40)	2c	1	0.1	99.0
41(39)	3a	1	0.1	99.1
42(39)	3e	1	0.1	99.2
43(39)	5d	1	0.1	99.3
44(39)	5e	1	0.1	99.4
45(39)	7b	1	0.1	99.5
46(39)	7g	1	0.1	99.6
47(39)	10c	1	0.1	99.7
48(39)	11a	1	0.1	99.8
49(39)	11b	1	0.1	99.9
50(39)	13c	1	0.1	100.0

* rank in brackets was adjusted for ties, i.e. all classes of same size have the same rank.

The high number of small classes relative to large classes can be represented graphically by plotting the size of the 50 sound classes against their relative rank (by decreasing probability of occurrence). The relationship fits a negative exponential function (Figure 54).

REPERTOIRE SIZE

Figure 55 illustrates the increase in number of classes found versus the increase in sample size. Since there was no sampling unit (i.e., recording sessions had variable duration and resulted in variable number of sounds), this figure was obtained by splitting the 1255 sounds in the sample in subsets of 50 (there was no new sound in the last five analyze :), beginning with the sounds from working tape 1, and ending with those from working tape 10. It suggests that most sound categories used by humpbacks during the study and in the area were found, as few new sounds were obtained in the last recording sessions.

Fagen (1978, p. 32) defines sample coverage as:

> "...t e robability that in a new, independent sar.ple f behavior, a randomly chosen act will belong · a type already represented in the initial sar le of I behaviors."

Sample coverage is the sum of the true probabilities assigned to each of the behavior types:

$$\theta = \sum_{i=i_1}^{i_y} p_i$$

Sample coverage itself cannot be directly estimated. However, one can estimate the average sample coverage for all samples of I acts from the animal's repertoire. In the present study, if N1 is the number of

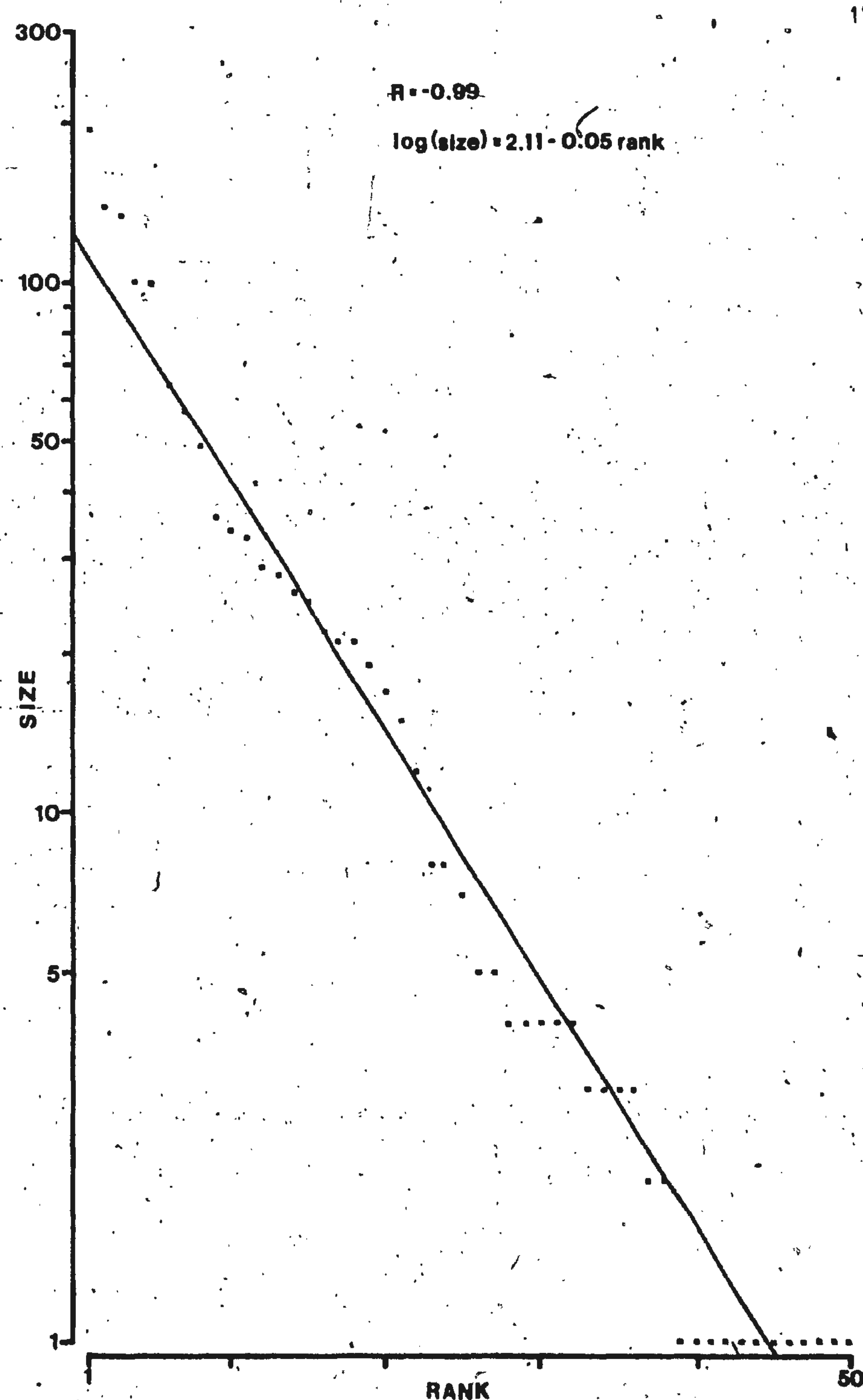


Figure 54. Relationship between logarithm of class size and rank for the 50 classes found in the study.

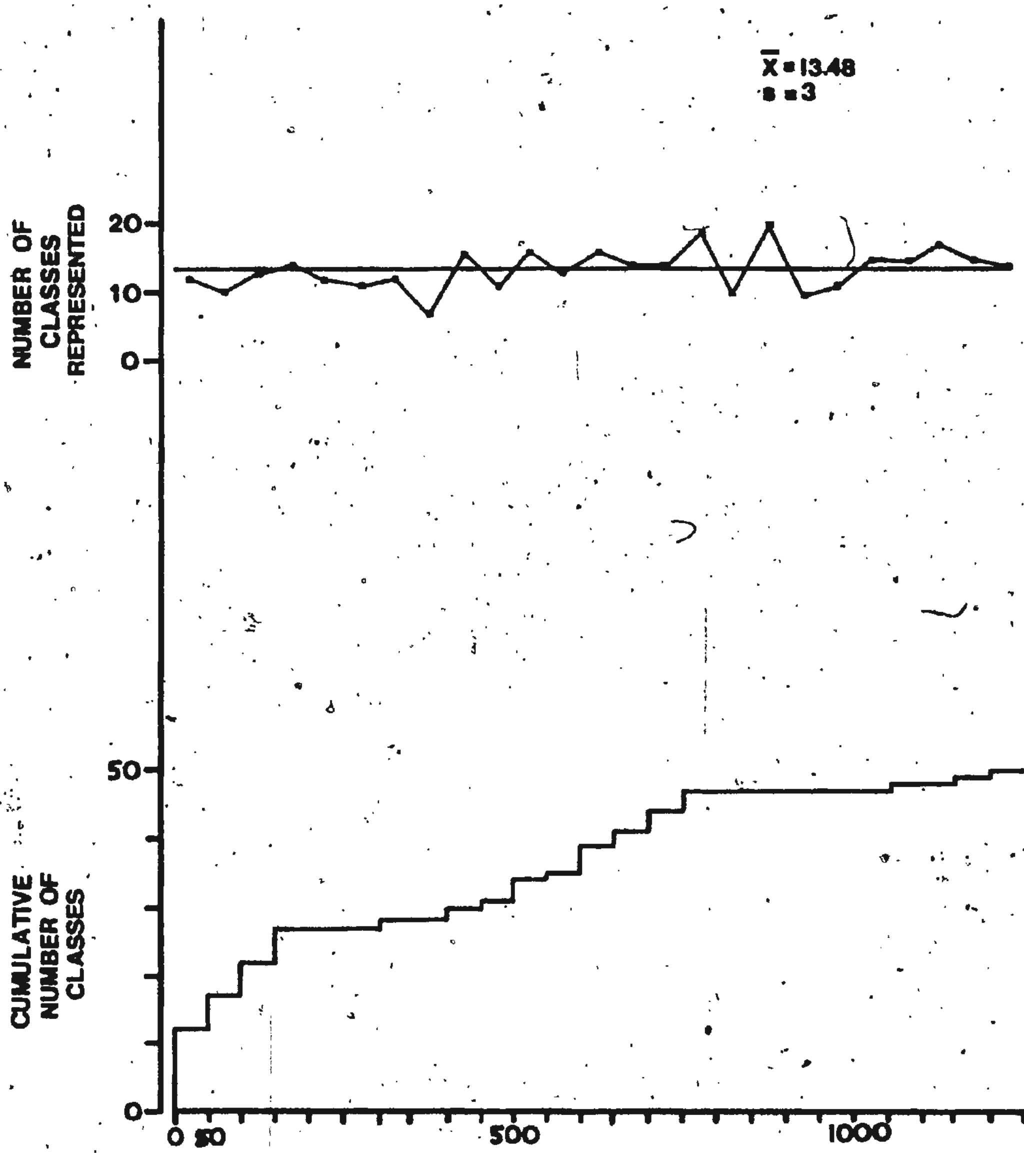


Figure 55. Number of different classes and cumulative number of classes for each block of 50 sounds analyzed.

classes with a single element,

$$\hat{\theta}_g = 1 - \frac{N1}{I} = 1 - \frac{12}{1255} = 0.99$$

The probability that a new case belongs to a sound class not yet defined is only 0.01, and the coverage is essentially complete.

DISCUSSION

CLASSIFICATION PROCESS

Data coding. Considering the complexity of the humpback whale's acoustic repertoire and the degree of variability between and within the different sound categories, data coding proved to be fairly adequate. The 936 cases used in run 1 (Table 4, p. 57) were also analyzed in three other ways: (1) average linkage cluster analysis and squared euclidian distance (Wishart 1978) were used first on the discrete measurements; (2) then on the standardized discrete measurements; and (3) on the discrete measurements, after taking the logarithm of the measures of frequency. These results were not compared quantitatively. However a qualitative evaluation was made, and these methods were not as good as the method adopted here in discriminating the different categories.

Discrete measurements would certainly be useful in comparing similar sound classes, or in looking for signature and/or dialect information in a given class, but it is not likely that they would be sufficient for classifying such a complex repertoire. As mentioned in previous sections, methods based on measurements of fundamental frequency (e.g., Martindale 1980a) or on computing of regression lines (e.g., Clark 1983) were difficult to use with many of the humpback's sounds.

One major problem encountered during digitizing was the need to digitize many sounds twice (once for each of the two scales used). This was not due to the digitizing technique, but to the spectrograms available. It could have been avoided by printing all spectrograms in the 0-8 kHz range, with a logarithmic scale. Also, other models of spectrographs could have been used: a linear scale from 0-5 kHz would have been acceptable.

This digitizing method was designed to retain as much as possible of the sounds' structure. Frequency contour, shape, duration and harmonic structure were taken into account. Except when much noise was present, frequency modulation was also well measured. Herman & Tavolga (1980) emphasized the frequency discrimination capabilities of odontocetes and noted that for birds and mammals, frequency modulation was important in auditory communication. Taking into account what variables have been used in other studies, and what was feasible with the equipment available, I decided that losing some information on sound intensity, amplitude modulation and repetition rate was acceptable in coding the sounds. More parameters than in most studies were included, making it less likely that the characteristics of the sounds utilized by the whales were not measured.

Preliminary analysis showed that many sounds with very different acoustic properties ended up with very similar matrices after digitizing. The main reason was that many sounds had noise and/or harmonics (real harmonics or side bands caused by high repetition rate in pulsive sounds). Since all components were digitized, important factors like frequency of maximum intensity and frequency modulation were masked by the noise or harmonics. This can be solved by adding categorical variables for peak frequency and frequency modulation. In fact, the addition of these variables improved the results of cluster analysis in this study.

It would probably be still better if the categories used in these additional variables had finer gradations. One problem with these additional variables was that their weight relative to the digitized matrix was not constant. Short and/or narrow frequency sounds scored relatively little in the data matrix; thus, the 48 additional variables carried much weight. Variables on peak frequency and/or frequency modulation had much less effect in the clustering process of longer sounds, if rich in low frequencies. Correction for this could have been done by making the number of points sampled (here only three: start, middle and end) proportional to the duration of the sound, by taking measurements every 0.1 sec, for example. However, by doing so one would face the same problem as Martindale (1980a): the end of shorter sounds would be compared with the beginning or middle sections of very long sounds. [1]

There is another way to account for sound amplitude and frequency modulation: sound intensity could be entered in each cell of the data matrix, as in Koeppl et al. (1978). These authors coded their sounds manually, and sound intensity was coded in four levels. Manual coding is time consuming, and would be subject to difficult decisions in ambiguous cases. There is also an increased risk of introducing errors during data transcription. This coding could also be done automatically using optical devices on spectrograms. Ledley (1964) and Pickstock et al. (1980) used image analyzing computers to digitize sounds from spectrograms in a rapid and accurate manner. Ledley's approach is in two steps. A scanning instrument first digitizes the picture at high speed (many degrees of darkness are recognized). Data can then be measured

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[1] It would be preferable to digitize the middle section of sounds lasting more than 2 sec, instead of the first 2 sec. This would insure that only corresponding portions of the sounds are compared. However, this was not considered an important problem in the present study, as there were very few (44) sounds longer than 2 sec, and they were relatively constant over most of their duration.

directly from the computer's memory. Ledley also suggested ways to compare images that could be adapted to establish similarity between whale sounds. The method used by Pickstock et al. (1980) also recognizes different grey values (i.e., intensity values). Results could be affected by variations in sound intensity due to distance and to fine adjustments of the mark level of the spectrograph. Sounds can also be digitized directly from magnetic tapes, using Fast Fourier Transforms (G. Silber, pers. comm.; Goedeking 1983). By coding for sound intensity in each cell of the matrix, one would avoid problems such as relative weight of some variables when comparing sounds of different duration.

The number of lines and columns in the matrix was a compromise between accuracy and amount of data. It proved to be generally adequate, but the number of columns could be increased. Short sounds like classes 3c, 4a and 4b were not very well covered by the grid used in this study. Clustan will not handle more than 400 categorical variables, but programs to compute similarity coefficients are easy to write, and the results can be fed into Clustan. Also, the increase in data caused by larger number of columns in the matrix could be compensated by a reduction in the total duration sampled: by sampling 1.7 sec instead of 2 sec, 54 sounds instead of 44 would be incompletely covered (an increase of less than 1%). This would allow for a increase in sampling rate from 0.1 sec to 0.085 sec, with the same amount of data.

Aural impression was sometimes heavily affected by repetition rate in pulsive sounds. It is not known if humpback whales have a good sensitivity for discriminating repetition rates. Odontocetes are known to be extremely sensitive to time intervals between their echolocation clicks. The inclusion of repetition rate and of changes in repetition rate in the variables, as in Thomas & Kuechle (1982), would most certainly improve any automatic classification process. It was not included in the present study because Clustan is not capable of handling variables with missing cases. In other words, one cannot include variables about repetition rate in Clustan, because such variables would be irrelevant for those cases that were tonal, noisy or noisy-tonal. However, it would be advantageous to include this information if a program that can handle "No Comparison" cases was used (as explained in Sneath & Sokal 1973, such programs would use repetition rate when comparing pulsive sounds, but would ignore it if any or both of the two sounds being compared were not pulsive).

Similarity coefficient. In general, the Jaccard coefficient behaved well. However, since it is computed on a cell by cell basis (see Appendix C), it was thought to be responsible for the splitting of some classes in many very small clusters, as in classes 2f-2i, 12a, 13a and 13b. These sounds were tonal, with or without harmonics, or pulsive with a fast pulse rate, resulting in the presence of side bands on the spectrograms. In other words, their spectrograms were characterized by narrow band(s) of energy. Even when such sounds had a similar shape, similar frequency modulation, and sounded similar to the human ear, they were still assigned very low similarity values if their frequencies diverged, even slightly. This shift in frequency reduced the number of matches between the sounds. A correlation-type coefficient, such as the Pearson product-moment coefficient, might be better at dealing with such sounds. It has some theoretical and empirical problems (Eades 1965; Wishart 1978; Pimentel 1979), but Sneath and Sokal (1973) suggested that with a large number of variables with the same dimensional and directional properties, as in the present study, its undesirable properties would not manifest themselves.

From the results, it is also obvious that duration had strong effects on the calculation of the similarity coefficient, chiefly for sounds with low frequencies (because of the logarithmic scale). Other factors (bandwidth, minimum and maximum frequencies, and chiefly for short sounds, peak frequency and frequency modulation) also affected similarity. Complex factors like internal structure (i.e., harmonics) and shape were also taken into account.

Clustering of the sounds would have been improved if the effect of size (mainly duration) had not affected the computation of similarity so heavily. It can be seen in Figure 32, p. 123 (Class 7d), that often variation in duration in a given class was caused by one part of the sound (here, the beginning), being very variable, while the rest of the sound was fairly stereotyped. Following a suggestion by Miller (1979), the sounds were centered in the 2 sec matrix before digitizing. This was successful, since most cases from class 7d were put in the same cluster, which would have been most unlikely if all sounds had been digitized with their beginning in the first column of the matrix (sounds that started similarly would have been clustered together, while variation in duration would have split class 7d in many clusters). This correctional measure, however, was not sufficient. Similarity among class members of different duration was still very low, which was one of the reasons forcing the selection of a threshold value of 0.45. This resulted in a high number of clusters (115). This could be corrected in the following manner: for each comparison (i.e., for each pair of sounds in the sample), one sound could be slid against the other on the [2] horizontal axis (time) in steps of 0.1 sec, and similarity computed at each step. The highest value of similarity would be used in cluster analysis. This method has been used in comparing amino-acid sequences in proteins (Gibbs & McIntyre 1970; Sackin 1971). Another way to decrease the effect of size on the computation of similarity would be to select a similarity coefficient less sensitive to this effect, such as the "shape difference" coefficient (Wishart 1978) or the Pearson product-moment correlation coefficient (Sneath & Sokal 1973; Wishart 1978).

Other approaches could also be considered in establishing similarity between sounds (e.g., Ledley 1964; Koeppl _et al._ 1978; Miller 1979; Pickstock _et al._ 1980; Goedeking 1983; Adret-Hausberger 1983). For a complex repertoire, the methods used by Ledley (1964), Pickstock _et al._ (1980) and Goedeking (1983) have the best potential.

Cluster analysis. Overall, cluster analysis performed better than the high number of clusters suggests. This is because most classes had been isolated in at least one cluster. Many small clusters contained extreme cases of classes that were defined in larger clusters. Average linkage is known for this tendency to produce small "nonconformist" clusters (Williams, Clifford, and Lance 1972, cited in Edelbrock 1979). Some classes appeared to be graded (see next section), and one would expect them to be split in many clusters, unless very low values of

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[2] The same sliding routine could be performed for frequency as well as time. This would measure contour similarity independent of absolute pitch (P. Tyack, pers. comm.). It is not known at this point, however, if sounds of similar shape but different pitch are recognized as a same signal by the whales.

similarity were used. Twenty-two of the fifty classes were well identified by cluster analysis (Table 7, p. 64), even if most of them had cases in more than one cluster. Ten classes were split in many clusters, but were not fused with other classes. Only eighteen classes were not recognized by cluster analysis, and most of them were very small. Such small classes are often not even considered. For example, McLeod (1982) omitted categories with one or two cases in his abridged coding. As indicated in the last column of Table 7 (p.64), when only classes occurring five times or more are considered, fourteen classes out of twenty-seven were recognized with a type "A" or "B" cluster, ten were still spread over many clusters, and only three were not recognized.

It is unfortunate that the author's impressions of the sounds had to be used in the classification process. This was made necessary by many factors. First, results are affected by the choice of clustering algorithm and similarity coefficient (Pimentel 1979). Second, the quality of data (which was unknown here, data coding being experimental) (Martindale 1980a), and the category structure present in the data (data would be clustered even if no category structure was present, Cormack 1971; Martindale 1980a) also affect the outcome of cluster analysis. Finally, no classification of humpback sounds existed. In fact, the author's impressions were not only used to check the results of cluster analysis, but also to improve on it and reach the final classification adopted here. This was because cluster analysis did not produce results acceptable as a definitive classification of the sounds. Weaknesses in data coding, and high variability in many of the classes, appeared to be the main factors for this, and were discussed previously. Consequently, similarity between sounds was often low, and the threshold value of similarity was only 0.45. Many classes were split in many clusters, and a further reduction of the similarity threshold would result in the fusion of clusters judged different by the author, before clusters representing the same class could be fused. Even at this level, classes that were later differentiated using criteria poorly represented in data coding were often found in the same cluster. Yet, cluster analysis was very useful in reaching the final classification. Factors that were not well measured were known, and the effect of variation in duration (and in some cases bandwidth) were recognized early. By using a large number of clusters, the work was mostly to fuse clusters that sounded or looked similar, which was easier than having to deal with 1255 cases. Since the author was left with only a few variables to consider (e.g., repetition rate and, sometimes, bandwidth and frequency modulation), it was easier to insure consistent decision making.

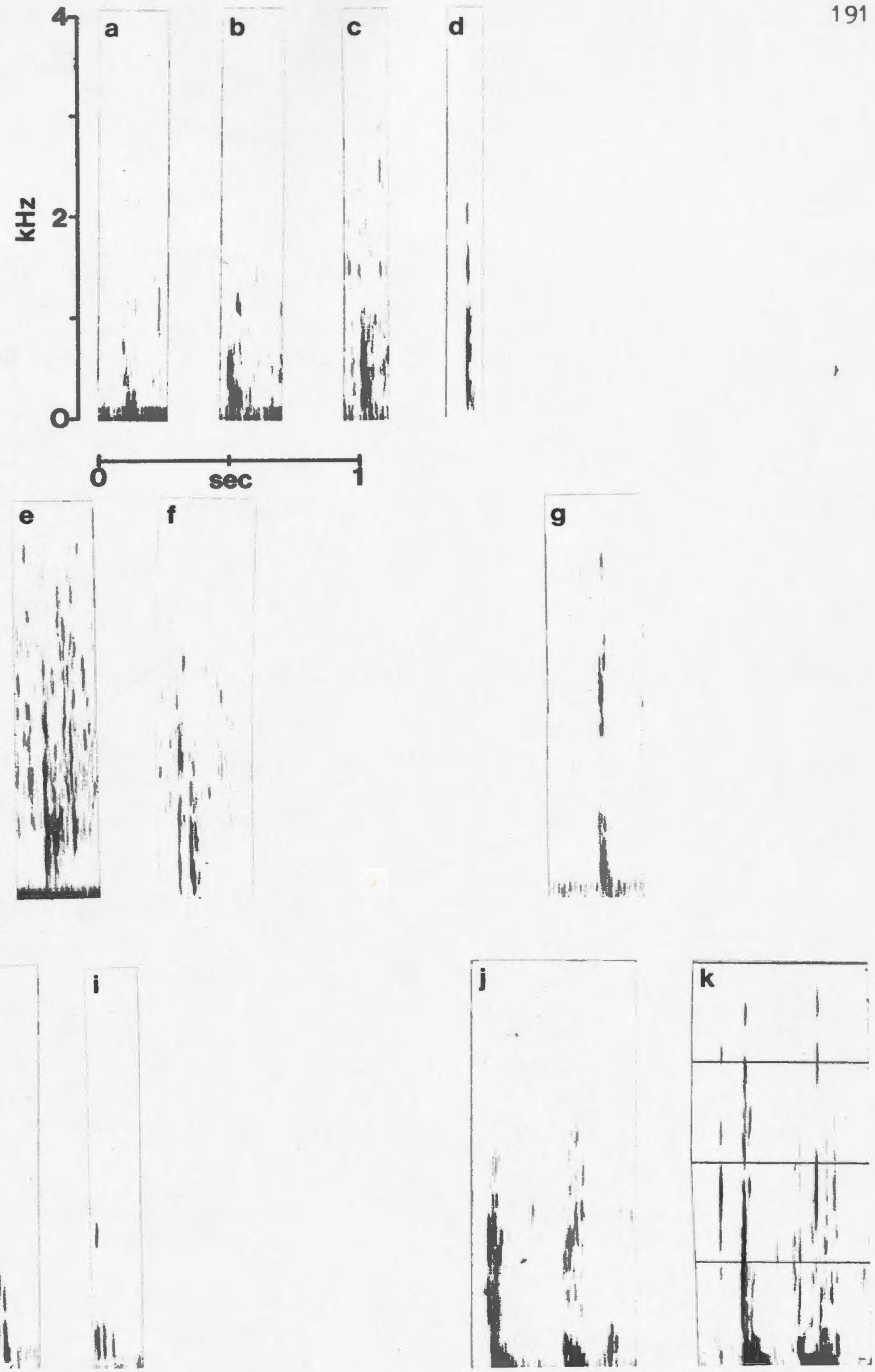
THE HUMPBACK'S REPERTOIRE

Variability within sound classes. As mentioned in the Introduction, there are many possible sources of variability for each class: within and between individual variability (including age and sex effects), group variability and maybe population variability. This last source was not involved here, as all sounds were recorded from the same population. Seasonal and long-term temporal changes are two other possible sources of variability. It is difficult to assess the seasonal variability. I do not believe that it was a major factor because most 1979 sounds were recored in August, as well as many 1980 sounds. Date of recording was not included in this analysis, and therefore seasonal variation will not be assessed until this is done. I did not compare the probability of occurrence of each class for 1979 and 1980. However, Tyack (1982) found that social sounds changed little over three years in Hawaii.

Signal directionality can affect greatly the frequency content and amplitude of signals (Schevill & Watkins 1966). It is not known if humpback sounds are directional. Answering this question was attempted in the present study. Sounds did not appear to be directional, but the identity of the vocalizing animal was not certain. However, distance certainly induced variability in the sounds. Bandwidth is the most affected. Since high frequencies have a higher rate of attenuation, they can drop out of distant sounds (Payne & Webb 1971; Watkins 1974; Wiley & Richards 1978 and 1982). Duration can also be affected, if either the beginning or the end of a sound is of lower intensity (Leger et al. 1980). This was partially controlled by digitizing only sounds with a good signal-to-noise ratio. But as can be seen in Figures 31 and 32 (p. 120 and 123), sounds can still be loud enough to be digitized, but be altered by distance. The logarithmic frequency scale reduced the effects of this type of variation (bandwidth) on the computation of similarity.

In true graded signals, variation within class carries information. Not knowing the importance of the other sources of signal variability, it is difficult to identify graded signals. An important characteristic of graded sounds is the presence of intermediate cases between categories. Using this criteria, the following classes could be part of a continuum. Classes 4a, 5a and 9a could be part of a continuum varying along many axes: bandwidth, duration, and dominant frequency (Figure 56). Classes 13a, 13b and 3a could also be along a continuum (Figure

Figure 56. Gradation between classes 4a, 5a and 9a. Class 4a had a variable bandwidth (a-g). Some of the cases with a wide bandwidth had most of their energy in very low frequencies (g) and were similar to the sub-units of class 9a sounds (j-k). Two or three sub-units were present in other cases (e-f), making them very similar to the shortest cases in class 5a (h-i).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h
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j
k

57): sounds with gradually lower peak frequencies and lesser rate of frequency downsweep could be found. Finally, classes 5b, 7a, 7c, 7d, 7e, 8a, and 10b also seem to vary along a continuum. Intermediate cases are present between classes 5b and 7a. In general, the gradation from 5b to 7a consisted of an increase in duration, a lowering of peak frequency, and the presence of a frequency upsweep toward the end of the sounds (Figure 58). Classes 5c-5e and 7b could also be seen as variations on 5b and 7a. There was a gradation between classes 7a and 7c, characterized by the disappearance of the relatively high frequency (around 1 kHz) portion at the beginning of 7a sounds. Class 7c graded in class 7d with the addition of a pulsive portion of relatively constant frequency, narrow bandwidth and slow pulse rate at the beginning of the sounds. It was very short in some class 7d sounds, which were clustered with class 7c. But it was very long in others (Figure 58). Class 7d graded in class 7e, with cases having higher peak frequencies, and in class 8a, with cases having little increase in peak frequency and bandwidth in their last portion. Class 7e also graded in class 10b, which had a faster repetition rate and was usually longer (Figure 58).

The decision of splitting these graded series in many classes was subjective. One reason was that sounds that are graded on one or more of their acoustic properties are not necessarily perceived as graded by the animal. The animals may not perceive and/or not use all the variation (Green & Marler 1979), and be more sensitive to between classes variability than to within class variability (Marler 1975). Even if the sounds are part of a real continuum, the distinction of a certain number of classes is useful, since these signals should have different meanings.

Figure 57. Gradation between classes 13a, 3a, and 13b. Sounds in class 13a differed somewhat in their bandwidth, their peak frequency and their rate of frequency change (a-d). Some cases were difficult to distinguish from class 3a (e-f) and 13b (g-i).

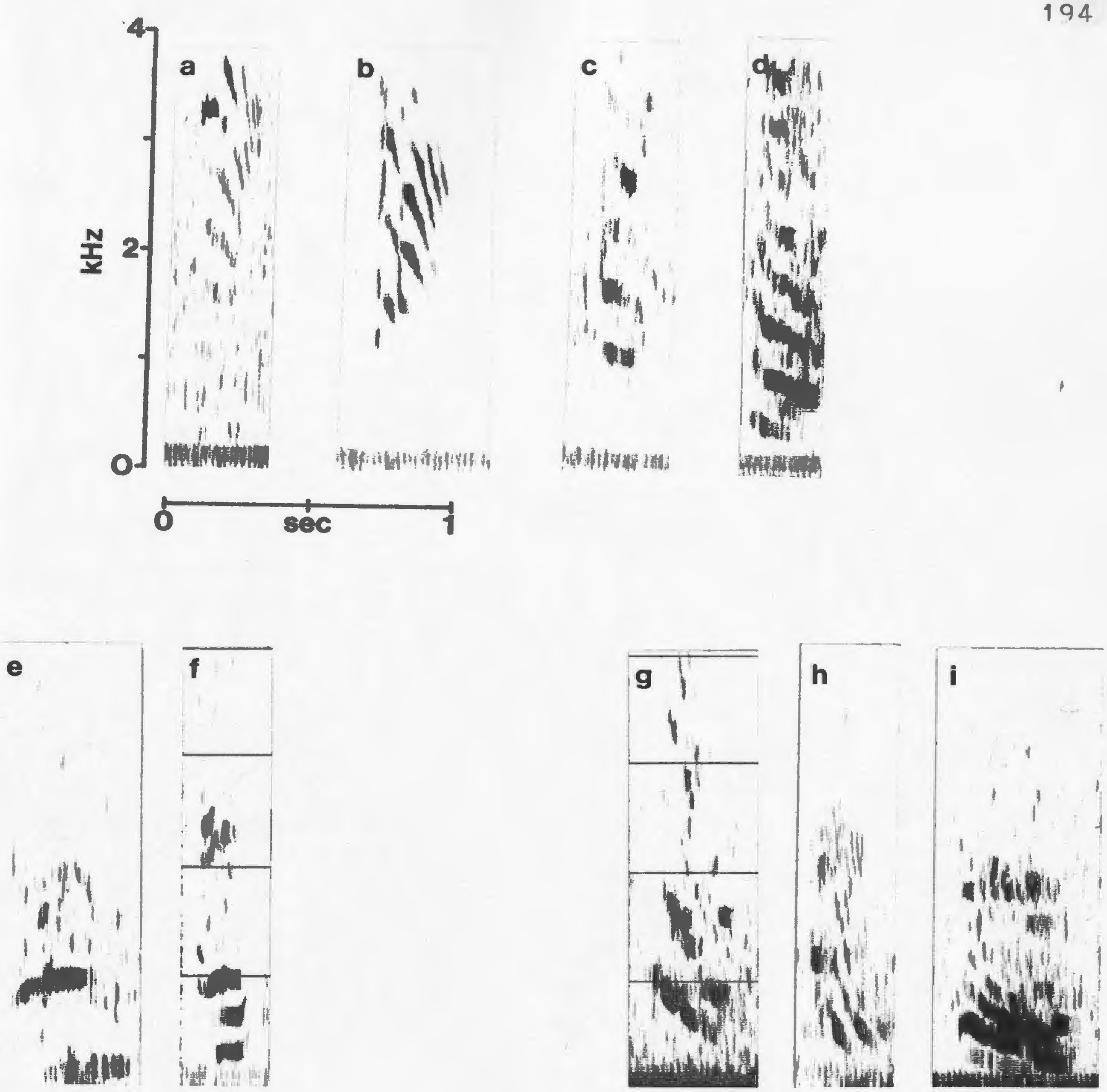
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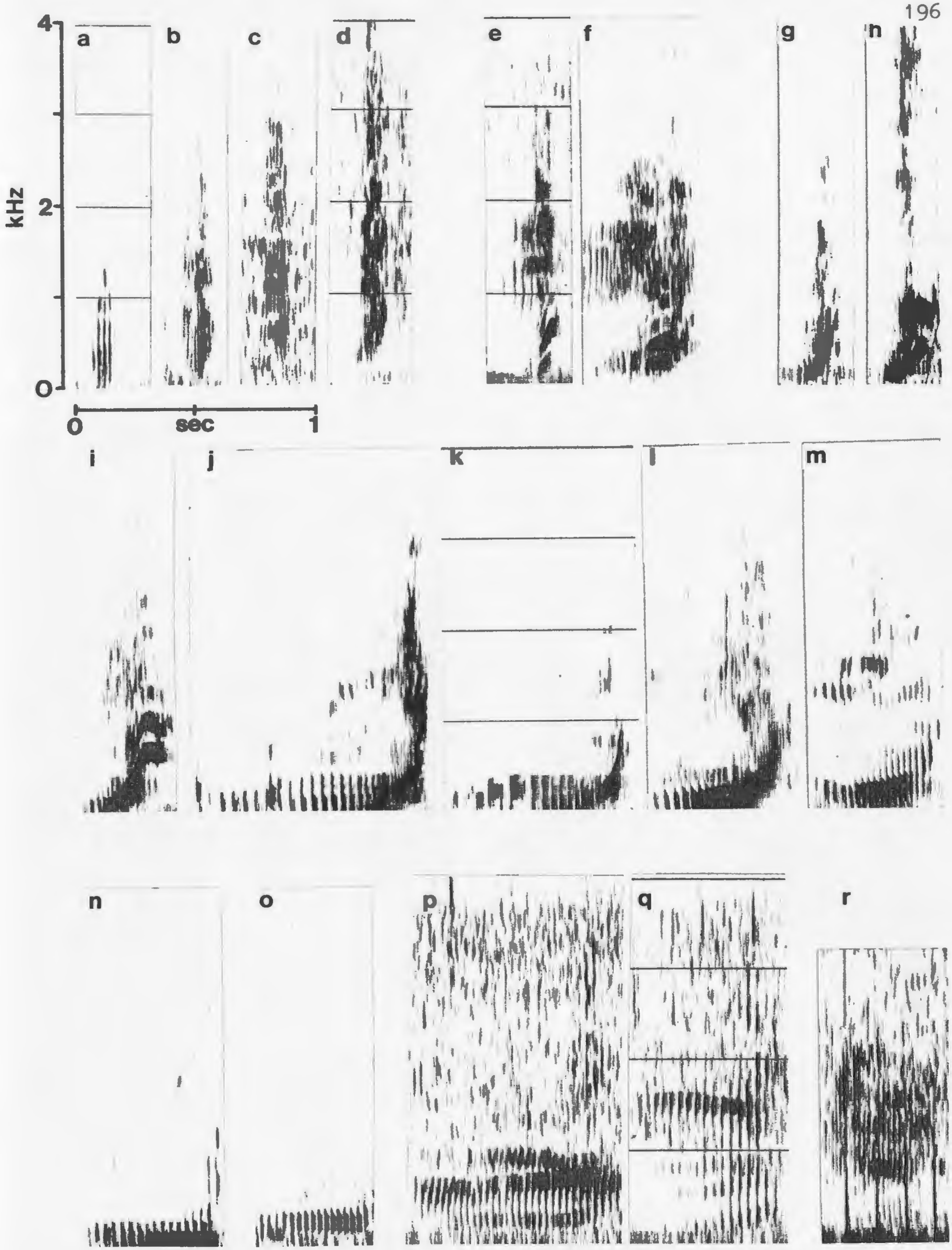
Figure 58. Gradation between classes 5b, 7a, 7c, 7d, 7e, 8a and 10b. Class 5b had a very variable bandwidth (a-d). Some cases were very similar to 7a (e-f), which were usually longer and started with a pulsive section around 1-2 kHz, and to 7c (g-h). Some cases in class 7d (i-m) were very similar to 7c, their low-frequency beginning being of very short duration. The increase in repetition rate toward the end of 7d sounds was less important or even lacking in some cases (i-m). These cases graded in class 8a (n-o) when the terminal frequency upsweep was also reduced, or in class 7e (p-q) when peak frequency was higher. Class 7e graded in class 10b which were usually but not always longer and had no frequencies below 0.5 kHz. Other cases had slower repetition rates



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There were two other arguments in favor of splitting these series. First, the distribution of sounds along the continuum was not homogeneous. Types that were abundant were linked to each other by rarer intermediates. Second, even if there were only subtle variations between the intermediate cases and the classes that bordered them, more substantial variations were found between the two bordering classes, making it difficult to fuse them into a single category. This is even more true when there was a chain of signals grading into each other. For example, it does not seem appropriate to put class 5b in the same category as 8a, even if a chain of intermediates can be found between the two. Playback of synthesized sounds would help deciding if these series are graded, or perceived categorically (Byrne 1982). Other classes may also be graded, since many classes had important variation in one or more variables.

<u>Repertoire size.</u> The asymptotic nature of Figure 55 (p. 178) suggests that most of the classes used by humpback whales in Newfoundland waters in summer and fall have been sampled. The slight increase in the last part of the curve might be due to a different recording context. These sounds were recorded late in season (October 1980). Groups appeared to be larger and more stable than in summer. These sounds (classes 5e, 7b, 10c) were recorded only once.

The sample coverage estimated with Fagen's (1978) technique also indicated that few classes would be discovered by increasing sample size. However, this estimate is based on the number of classes with only one element, which might be considered the most uncertain classes of the repertoire. First, sounds that have been recorded only once might have been produced by other species of whales. It was probably not the case, since often they were in a sequence of humpback sounds, and since their frequency characteristics are like those of better recognized humpback sounds. Because they are so rare, the identification of these classes is also more subjective than for larger classes. Often, they were not even revealed by cluster analysis. Yet, since this estimate agrees with Figure 55, it is likely that the present catalog is virtually complete for the years, season and the area studied.

The 50 classes found in this study are not the complete repertoire of the population studied. Only one communication channel was studied, and humpbacks are likely to use others as well, notably the optical channel (see the Introduction). Since social structure, reproductive status and activity vary seasonally in this species, the present sample must be considered incomplete. Yet, this number of behavior types is higher than what is reported for most species. Moynihan (1970) reviewed studies in animal communication and reported 16-37 displays (total for all communication channels) for mammalian species. No species was found to have as many as 40 or 45 different displays. However such arguments rest in part on the difficulty of defining displays. For example, Schleidt (1973) recognized 59 classes in a species that was given 37 displays by Moynihan (see Hailman 1977). Fagen (1978) also classified 12,211 behavior acts in 69 behavior types, in a study of domestic cat (Felis catus).

It is still possible that some categories have been split in many classes in the present study, since classification was done only on the signals' acoustic properties. Green & Marler (1979, pp. 92-93) warned that:

"Every signal can vary along the dimensions that physically

> describe it. Variations in some, however, may fail to be perceived. Thus, not every bit of the signal-pattern information theoretically available is necessary assessed or utilized by the receiver."

In the present classification, when doubt existed, two categories were recognized. Since this catalog will have to be tested in correlation studies and playback experiments, it was judged preferable to split: it will be relatively easy later to join classes that are found identical.

<u>Probability of occurrence of the different classes.</u> It is obvious that humpbacks use some sound classes much more often than others (Figure 54 p. 177). Studying human written language, Zipf (1935) found a linear relationship between the logarithm of the frequency of use and the logarithm of the rank of the syllables or words of a language. Moles (1963) assumed that Zipf's law, as it is known, applied to animal signals as well. With data on rhesus monkey signals however, Schleidt (1973) obtained a linear relationship by plotting the logarithm of frequency against the rank instead of its logarithm. McLeod (1982) with pilot whale vocalizations, and this study, also found that a plot of rank against frequency fits a negative exponential function.

It is not known if the differences in frequency of use found in this study are due to the sampling technique, i.e., if frequently used sounds occurred in situations better sampled. This probably account for part of the variation in class size. Sound production was found to be dependent on context in other studies of cetacean sounds. For example, Payne & Payne (1971) reported a much higher rate of sound production during night for right whales, while sound production was extremely low in small groups of humpback whales (Tyack 1982) and for sperm whales out of acoustic range of conspecifics (Watkins 1980). The difference might be qualitative as well as quantitative. Distance between whales and boat may also have affected the observed frequency of occurrence of the different classes: sounds composed of high frequencies, for example, will not be recorded as far as low frequency sounds. Consequently, whales producing low frequency sounds were more often in the recording range. Sounds that attenuate fast are probably undersampled in this study. This was partially taken into account during digitizing, by selecting only sounds with good signal-to-noise ratio. This eliminated many low frequency sounds obviously coming from distant whales. It should be noted however that the selection of sounds to digitize was not strictly random. It might be more informative to compute the same curve as in Figure 54 from all identifiable sounds in the original recordings, although the bias against high frequency sounds, probably used in short-distance communication, will be increased.

The relationship found between probability of occurrence and rank also suggests that part of the variation is inherent to the communication system. Schleidt (1973) gives many possible reasons for high probability of occurrence of some signals. The first reason is a special role in the grammar, as for signals that start, maintain or terminate a sequence of interactions. There can also be influences from factors other than communication, as sounds can have other functions than communication. An example of this is class 1a (blows), which ranked fourth in the repertoire, but also serves a respiratory function. High probability of use can also be an adaptation to environment noise, or to increase localizability of the sender.

This does not mean that rare types are unimportant. In fact, in information theory, the least frequent signal carries the greatest amount of information (Moles 1963; Schleidt 1973; Wilson 1975).

Comparison to previous results. As in Kinne (1975) and Clark (1983), the sounds could be assigned to three production modes. Two were obvious: respiration noises (e.g., blows, classes 1a and 1b) and percussion noises (slaps resulting from the impact of the whale's entire body, flipper or tail on the surface, as in class 4b). Like Clark, I assumed that the other sounds were vocalizations or calls, with the possible exception of class 7f, which might be similar to the baleen rattle reported by Watkins & Schevill (1976) for right whales (although no whale was seen with the baleen above the surface at that time), and maybe class 6a, which, with its exclusively noisy nature, does not sound like a vocalization.

Comparison with other investigations is difficult. Not all published reports on whale vocalizations are illustrated with spectrograms. It is very difficult to compare aural impressions and spectrograms with other authors' verbal descriptions or oscilloscope displays. When spectrograms are used, they frequently have a different scale and analysis filter. In many studies of humpbacks and other mysticetes, low frequency ranges (often 0-1 kHz) and narrow analysis filters were used. This can affect greatly the appearance of sounds. For example, frequency modulations of as little as 60 Hz (Schevill & Watkins 1972; Cummings et al. 1974; Clark 1983) appeared very marked on spectrograms of minke whale and right whale sounds, because of the narrow frequency range analyzed, while such frequency modulation was not even recognized in the present study. Similarly, the individual clicks of many pulsive sounds were resolved here, while a harmonic structure would usually be present if narrower analysis filters had been used. Also, many of the terms found in description of whale sounds (e.g., moan, grunt, growl, chirp, pulse) are used with different meanings, and are rarely defined.

A few classes were easily identified to sounds previously reported in the literature. It was indicated in the description of these sounds. This is summarized in Table 22, which associates the equivalent (or potentially equivalent, in brackets) classes found in this study and sounds reported elsewhere. The last column gives the rank of these classes in the present study. Most sounds described by other authors that could be associated with my classes were fairly common in the present study: they ranked first, fifth, sixth, eigth, ninth, tenth, seventeenth and twenty-third (in this last case, 4a, it was mentioned earlier that it was undersampled). Classes that were only tentatively associated with reported sounds were sometimes common (e.g., rank = 2, 3, 5, 6, 10, 14, 17, 20), or relatively rare (e.g. rank = 25, 26, 28, 33, 37). Two of these studies (Beamish 1979; Winn et al. 1979) dealt with humpback whales entangled in fishing nets. Both these authors found a very low rate of sound production for humpbacks in Newfoundland waters, which was corroborated in the present study, even if quantitative data on production rate were not analyzed. However, small sample size (two whales in Winn et al. 1979, and one in Beamish 1979) probably explains why they found less diversity in sound types and no medium frequency sounds in their data, compared with the humpback song. A few of the sounds they identified were similar to song units, but they noticed a slower repetition rate (the sounds were pulsive) in northern waters. But considering their sample size and the variability found in most classes of the present study, this conclusion is uncertain.

Table 22. Comparison between the 50 classes identified in this study and previously reported humpack social sounds.

The sounds are grouped into general types (see Table 1, pp. 23-24). References are listed at the bottom of the table. Sounds' description were obtained from each publication, and/or by looking at the spectrograms (RR stands for repetition rate, in pulses per second). These sounds could not always be matched to the sound classes identified in this study. Possible matches are indicated in brackets.

SOUND TYPE	REF.	DESCRIPTION	ILLUSTRATED *	CORRESPONDING CLASS	RANK
loud exhalations	[1]	wheezing blow	S	1b	10
	[4]	shriek		(1b)	10
	[4]	trumpetting		(1b)	10
flipper or tail slaps	[4]	broadband pulse		4b	23
various moans	[6]	moan with fast RR: 80-15	S	(7f,8d,8e)	33,26,25
	[6]	pulsed moan, slow RR:25-50	S	8a	8
	[6]	pulsed moan ending in Yup	S	7d	1
	[6]	pulsed moan ending in moan	S	(8b)	17
	[5]	ratchet, increasing RR	SO	8b	17
	[4]	moan			
grunts	[4]	grunt			
yups	[6]	Yup, fast RR	S	7c	5
	[4]	yelp		(7c)	5
chirps	[6]	pure tone or broadband	S	(2h,3c)	28,2
cries	[6]	freq modulated	S	(2b,2i)	28,28
clicks	[2]	pulsive	SO	(4a)	6
	[2]	double-click		(4a)	6
	[6]	narrow-band		(4a)	6
	[6]	wide-band	S	4a	6

(continued on next page)

Table 22. (Continued)

SOUND TYPE	REF.	DESCRIPTION	ILLUSTRATED *	CORRESPONDING CLASS	RANK
click trains	[2]	clicks	S	(7e)	20
	[5]	click train	O		
	[5]	click train	O		
	[5]	click train	SO	10a	9
	[4]	pulse train, RR: 1, plus .04-1.2 kHz noise			
	[4]	pulse train, RR>1, uneven amplitude			
	[7]	pulse train		(7e)	20
others	[1]	(no name)	S		
	[2]	white-noise blast	S	(6a)	37
	[2]	pulsive	S		
	[3]	whooshes	S		
	[5]	pulsed sounds	SO	(4a,13b)	6,14
	[4]	pulses, low and narrow			
	[7]	type 1	S	7d	1
	[7]	type 15	S		
	[7]	type 25	S		
	[8]	type A	S		
	[8]	type B	S	(5b,7c)	3,5

* S = spectrogram O = oscilloscope display

[1] Watkins, 1967
[2] Winn et al., 1970
[3] Perkins & Whitehead, 1977
[4] Thompson et al. 1977
[5] Beamish, 1979
[6] Winn et al. 1979
[7] Lawton, 1979
[8] Tyack, 1982

CONCLUSION

In trying to design an automatic method to classify humpback whale social sounds from Newfoundland waters, measurements usually taken on animal sounds were found inadequate. Pickstock et al. (1980) also found that measures such as mean, maximum or minimum frequency do not quantify patterns of frequency changes adequately. The new data coding, used with average linkage cluster analysis and the Jaccard similarity coefficient, was an improvement. The classification obtained this way could not, however, be used as a final classification of the sounds. The results of cluster analysis and the author's aural and visual impressions of the sounds were compared in establishing the catalog of humpback's social sounds. The final classification adopted is much more complex (50 different categories) than previous reports (e.g., Schevill 1964; Beamish 1979; Winn et al. 1979) had suggested. This is due to the very low rate of sound production in Newfoundland waters and to the small sample size used by these authors.

The digitizing technique could be improved to include variation in sound intensity. Modifications in the computation of similarity, to reduce the effect of duration on similarity, would also improve performance of cluster analysis. Other multivariate techniques used in numerical taxonomy (e.g., ordination, principal component analysis) could also be used, and results compared. They may not be appropriate for this data set, the high number of sound classes making visual examination of two- or three-dimension plots very difficult (e.g., Clark 1982). The method used here probably is only an intermediate step in the progression toward rapid and efficient coding and classification techniques for sounds. As discussed above, new techniques will account better for sound intensity (i.e., Ledley 1964; Pickstock *et al.* 1980) and will not require spectrograms (Goedeking 1983).

This catalog can only be considered a beginning, since it was based exclusively on the acoustic properties of the sounds. Data are needed on the possible function of the signals. A direction finding device (Clark 1980) could be used to determine what whale (or group of whales) produced the signals, making it possible to correlate sound classes with behavior types. Playback experiments (Clark & Clark 1980; Tyack 1983) should also be used to determine the number of different sound classes recognized by humpbacks, as well as their function.

It would be interesting to compare these sounds with social sounds recorded in the same situation but from other populations (e.g., humpback whales feeding in Alaskan waters). Humpback of different populations have a different song, yet song structure is the same (Payne *et al.* 1983). It is not yet known if different populations share at least part of their social sounds. Comparisons could also be made with social sounds recorded on the breeding grounds. Larger groups there, as well as probable hormonal differences, occurrence of courtship, breeding and competition between males should mean a different frequency of use for at least some sound categories. It would be conceivable that some social sounds are used exclusively on the feeding or the breeding grounds.

Possible variation (both in structure and frequency of use) during the season or between years was not investigated here. Few sounds (179) from 1979 were digitized, and they did not seem different from the sounds recorded in 1980. This is also what Tyack (1982) found. This aspect should be specifically addressed in the future. Few recordings of humpbacks wintering in Newfoundland are available (J. Lien, pers. comm.). A better coverage around the year would be necessary in a study of variation in rate and type of vocalizations in time. If variation was found, it could be related to the variation in humpback's song (Payne et al. 1983). This would necessitate a detailed study of the song's units, which is still lacking (R. Payne, pers. comm.).

Study of the syntax of the humpback's acoustic repertoire was not attempted. Such study is made difficult by the fact that the number of whales involved in a sequence of sounds is impossible to determine. One is limited to study temporal association between sound classes, as in McLeod (1982). With a direction finding device, it might be possible to record sequences where the interactants are known. More detailed grammatical studies would then be possible.

Finally, the possibility of interspecific communication should be assessed. In a few occasions during the present study, humpback's behavior and rate of vocalization was affected by the presence of a school of odontocetes. Small sample size and lack of baseline data (rates of sound production were not computed, since not all sounds were digitized) prevented me from quantifying this effect.

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Appendix A
FREQUENCIES SELECTED FOR DIGITIZING

It was decided to sample 16 frequencies. One possibility was to distribute them at equal distance on the frequency axis of the spectrograms. However, R. Payne (pers. comm.) suggested a logarithmic spacing, since most species tested to date seem to discriminate frequencies on such a scale. Mysticete sounds recorded to date usually have strong emphasis in frequencies under 1000 Hz, and a matrix based on a linear frequency scale would not cover this region very well (only 2 frequencies below 1000 Hz (125 and 625 Hz) were selected in a first scheme, based on a linear scale). A logarithmic scale permits a better sampling of the lower frequencies. Payne & McVay (1971) and Beamish (1979) on humpback whales and Clark (1982) on right whales used the logarithmic scale for their spectrographic analysis. The first line was assessed at 125 Hz because of the amount of noise often prevalent in lower frequencies.

Since the spectrograms were printed with a linear frequency scale, the spacing between the frequencies to digitize had to be logarithmic. For this, I used a linear increase of the logarithms of frequencies. Arbitrarily, I chose to increase the logarithm of frequencies by .119, from the minimum value of 2.097 (which is log 125), because it yields 16 values in the 125-8000 Hz range, with the highest slightly lower than 8000 Hz.

Table 23. Frequencies selected for digitizing.

Log(freq)	Frequency (Hz)	Line number in matrix
2.097	125	16
2.216	164	15
2.335	216	14
2.454	284	13
2.573	374	12
2.692	492	11
2.811	647	10
2.930	851	9
3.049	1119	8
3.168	1472	7
3.287	1936	6
3.406	2547	5
3.525	3350	4
3.644	4406	3
3.763	5794	2
3.882	7621	1

Appendix B
DIGITIZING AND SAMPLING PROGRAMS

The following program in C language was written by Mr. Frank Pronk, programmer at the Faculty of Environmental Design, University of Calgary. It was modified by the author for digitizing on a logarithmic frequency scale. The modified version is given here.

Digitizing program (C language)

```
#include <sgtty.h>
#include <stdio.h>

#define NROW    16
#define NCOL    21

#define FREQ(x)         (x/1000.0*2.54/cm_khz)
#define TIME(x)         (x/1000.0*2.54/cm_sec)
#define UNTIME(x)       ((x/2.54)*1000.0*cm_sec)

typedef struct { double x, y }  Xy;

FILE    *digit, *ofile;
double  cm_sec, cm_khz;
int     matrix[NROW][NCOL];
struct  sgttyb oldmode;
struct  sgttyb newmode = { B1200, B1200, '\b', '}', CRMOD|LCASE|BS1 };
Xy      origin;
Xy      maxfreq, minfreq;
struct  {
        Xy      low, peak, high;
} beg, mid, End;

main(argc, argv)
char **argv;
{
        setbuf(stdout, (char *)NULL);
        if(argc != 2) {
                fprintf(stderr, "usage: log file_name\n");
                exit(1);
        }
        if((digit = fopen("/dev/digitizer", "r")) == NULL) {
                fprintf(stderr, "sound: can not open /dev/digitizer\n");
                exit(1);
        }
        if((ofile = fopen(argv[1], "a")) == NULL) {
                fprintf(stderr, "sound: can not open %s\n", argv[1]);
                exit(1);
        }
        lock();
        getscale();
```

```
        while(1) {
                getparam();
                digitize();
                outmat();
                fflush(ofile);
        }
}

getscale()
{
        printf("enter x scale in cm / sec ");
        scanf("%f", &cm_sec);
        printf("enter y scale in cm / kHz ");
        scanf("%f", &cm_khz);
        printf("enter origin  ");
        getxy(&origin);
}

getparam()
{
        double time;
        double maxp;
        double minp;
        char buf[200];

        printf("\n\nenter comments and other data\n");
        printf("terminate with a control D\n");
        while(fgets(buf, sizeof(buf), digit) != NULL)
                if(buf[0] != '\n') {
                        printf("%s", buf);
                        fprintf(ofile, "%s", buf);
                }
        getpoint(&beg.low, "enter lowest frequency beginning of sound");
        getpoint(&beg.peak, "enter peak frequency, beginning of sound");
        getpoint(&beg.high, "enter highest frequency beginning of
                 sound");
        fprintf(ofile, "%.2f %.2f %.2f\n", beg.low.y,
                beg.peak.y, beg.high.y);
        getpoint(&maxfreq, "enter maximum frequency");
        getpoint(&minfreq, "enter minimum frequency");
        fprintf(ofile, "%.2f %.2f %.2f %.2f\n", maxfreq.x, maxfreq.y,
                minfreq.x, minfreq.y);
        getpoint(&mid.low, "enter lowest frequency, middle");
        getpoint(&mid.peak, "enter peak frequency, middle");
        getpoint(&mid.high, "enter highest frequency, middle");
        fprintf(ofile, "%.2f %.2f %.2f\n", mid.low.y,
                mid.peak.y, mid.high.y);
        getpoint(&End.low, "enter lowest frequency, end");
        getpoint(&End.peak, "enter peak frequency, end");
        getpoint(&End.high, "enter highest frequency, end");
        fprintf(ofile, "%.2f %.2f %.2f\n", End.low.y,
                End.peak.y, End.high.y);
        time = End.peak.x - beg.peak.x;
```

```
	maxp = (maxfreq.x - beg.peak.x)/time;
	minp = (minfreq.x - beg.peak.x)/time;
	fprintf(ofile, "%.2f %.2f %.2f\n", time, maxp, minp);
	printf("origin at %d\n",
		(int)((origin.x + UNTIME((2. - time) / 2.))/10));
/*	printf("origin at %d\n", (int)(origin.x / 10));*/
	printf("\nenter sound data - terminate with a control D\n");
}

/*
 * print the matrix of digitized sounds
 */
outmat()
{
	register int i, j;

	for(i=0; i<NROW; i++) {
		for(j=0; j<NCOL; j++) {
			putc(matrix[i][j]?'1':'0', ofile);
			matrix[i][j] = 0;
		}
		putc('\n', ofile);
	}
}

/*
 * read a point from the digitizer
 * convert x and y to seconds and kilohertz
 */

getpoint(xyp, message)
register Xy *xyp;
char *message;
{
	if(message)
		printf("%s  ", message);
	if(getxy(xyp) == 0)
		return(0);
	xyp->x = TIME(xyp->x);
	xyp->y = FREQ(xyp->y);
	if(message)
		printf("%.2f %.2f\n", xyp->x, xyp->y);
	return(1);
}

getxy(xyp)
Xy *xyp;
{
	char buf[200];
	int x, y;

	while(1) {
		if(fgets(buf, sizeof(buf), digit) == NULL)
```

```
			return(0);
		if(sscanf(buf, "%d%d", &x, &y) != 2)
			continue;
		xyp->x = -x - origin.x;
		xyp->y = -y - origin.y;
		return(1);
	}
}

digitize()
{
	register int row, col;
	Xy point;
	double log10();

	while(getpoint(&point, (char *)0)) {
		row = 15.57 - ((log10(point.y * 1000) - 2.097)/ 0.119);
		col = point.x * 10. + 0.5;
/*printf("r=%d c=%d\n", row, col);*/
		if(row < 0 || row >= NROW || col < 0 || col >= NCOL)
			continue;
		matrix[row][col]++;
	}
}

/*
 * make sure the digitizer is not in use and then set
 * proper line speed and parameters
 */
lock()
{
	gtty(fileno(digit), &oldmode);
	if(oldmode.sg_flags & BS1) {
		fprintf(stderr, "sound: digitizer busy\n");
		exit(1);
	}
	stty(fileno(digit), &newmode);
}
```

Sampling program (APL)

```
     ∇ L SELECT R;I
[1]    Z←L[1]?L[2]
[2]    Z←Z[⍋Z]
[3]    I←⍴Z
[4]    Z←(I,1)⍴Z
[5]    ⎕EC 'FO ',R
[6]    Z
[7]    ⎕EC 'RO'
     ∇
```

Appendix C
JACCARD COEFFICIENT AND AVERAGE LINKAGE CLUSTER ANALYSIS

JACCARD SIMILARITY COEFFICIENT

The Jaccard similarity coefficient between cases i and k was computed according to the following formula (Wishart, 1978):

$$S = \frac{A}{A+B+C},$$

where A = number of attributes (cells) common to both cases
B = number of attributes present in case i and bsent in kk
C = number of attributes present in case k and absent in i

This coefficient is the total number of positive matches between two sounds divided by the total of the positive matches and the mismatches. It does not take the negative matches (number of attributes absent in both cases) (Sneath & Sokal, 1973; Wishart, 1978).

AVERAGE LINKAGE CLUSTER ANALYSIS

This is an agglomerative technique, which means that at the beginning, all cases are considered a different cluster. If there are n sounds, there are n clusters. In the first cycle similarity is established between each pair of sounds. At the end of this cycle, the two sounds with the highest similarity are fused. There are now n-1 clusters. In the second cycle, the similarity table is updated by computing the similarity between the new cluster and all the other clusters. In average linkage, this similarity is established in the following way: the similarity between the new cluster and any other one is the average of the similarities between each member of one cluster and all the members of the other cluster. At the end of this cycle, the two clusters with the highest similarity are fused. There are now n-2 clusters. This process will continue until all cases have been put in a single clusters, or until cycle n-1.

This process can also be described in the following manner (Wishart, 1978). If clusters P and Q have already been fused, then the similarity S(R,P+Q) between any cluster R and the new cluster P+Q is obtained from the formula:

$$S(R,P+Q)= \frac{NP}{(NP+NQ)} \times S(R,P) + \frac{NQ}{(NP+NQ)} \times S(R,Q) ,$$

where NP and NQ are cluster sizes, and S the average similarity between the two clusters, i.e. average of the similarity of each possible pair between the two clusters.

Appendix D
Characteristics of the 115 clusters

For each class, the number of cases (n), mean dominant frequency at three points (start, middle, and end of sound), minimum and maximum frequencies, and duration are given, with the standard deviation in brackets.

CLASS (n)	DOMINANT FREQ (kHz) START	MIDDLE	END	MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)
1	0.71	0.83	0.59	0.19	4.64	0.61
(86)	(0.51)	(0.29)	(0.50)	(0.08)	(1.34)	(0.15)
2	1.51	0.73	0.77	0.42	4.32	0.31
(11)	(0.57)	(0.14)	(0.25)	(0.13)	(1.87)	(0.10)
3	1.26	1.28	1.02	0.41	6.01	1.02
(36)	(0.38)	(0.55)	(0.68)	(0.18)	(1.62)	(0.21)
4	0.78	0.00	1.12	0.64	3.54	0.98
(1)	-	-	-	-	-	-
5	1.68	2.18	0.66	0.52	2.66	0.80
(1)	-	-	-	-	-	-
6	2.28	2.05	2.30	0.47	7.81	1.52
(6)	(0.91)	(0.64)	(0.68)	(0.20)	(0.33)	(0.09)
7	1.00	1.08	0.88	0.69	7.80	1.72
(1)	-	-	-	-	-	-
8	1.69	0.84	1.88	0.48	7.50	0.85
(5)	(0.94)	(0.07)	(0.44)	(0.17)	(0.32)	(0.36)
9	2.88	2.23	1.89	0.44	3.53	0.76
(1)	-	-	-	-	-	-
10	2.59	1.07	2.35	0.84	4.52	1.19
(1)	-	-	-	-	-	-
11	1.53	0.77	1.51	0.66	2.52	1.59
(1)	-	-	-	-	-	-
12	0.82	0.91	0.92	0.46	2.92	2.18
(1)	-	-	-	-	-	-
13	0.82	0.80	0.60	0.50	2.09	1.74
(3)	(0.24)	(0.05)	(0.19)	(0.18)	(0.35)	(0.36)

(continued)

CLASS (n)	DOMINANT FREQ (kHz)			MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)
	START	MIDDLE	END			
14 (3)	0.94 (0.17)	1.40 (1.10)	0.51 (0.21)	0.22 (0.16)	6.47 (2.26)	0.48 (0.03)
15 (2)	1.33 (0.95)	0.64 (0.03)	2.75 (1.85)	0.52 (0.01)	6.59 (0.05)	0.85 (0.30)
16 (1)	1.70 -	1.86 -	1.88 -	0.31 -	7.62 -	1.31 -
17 (1)	0.77 -	0.75 -	0.76 -	0.46 -	7.65 -	0.61 -
18 (1)	1.15 -	0.71 -	0.49 -	0.42 -	5.83 -	1.22 -
19 (1)	1.04 -	1.00 -	0.67 -	0.57 -	7.30 -	0.79 -
20 (1)	0.65 -	0.98 -	0.76 -	0.18 -	7.64 -	1.17 -
21 (1)	0.43 -	1.01 -	1.01 -	0.36 -	8.13 -	1.32 -
22 (1)	1.34 -	1.18 -	1.31 -	0.47 -	5.16 -	1.20 -
23 (1)	2.74 -	0.00 -	1.73 -	0.81 -	8.04 -	0.65 -
24 (1)	0.80 -	0.69 -	3.66 -	0.43 -	7.41 -	0.39 -
25 (1)	2.83 -	2.96 -	2.60 -	0.72 -	7.47 -	0.83 -
26 (1)	1.02 -	1.17 -	0.56 -	0.50 -	6.70 -	0.85 -
27 (3)	2.23 (0.64)	1.17 (0.36)	3.57 (1.71)	0.55 (0.05)	5.31 (2.74)	0.47 (0.16)

(continued)

CLASS (n)	DOMINANT FREQ (kHz)			MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)
	START	MIDDLE	END			
28 (1)	0.75 –	3.59 –	2.30 –	0.39 –	7.89 –	1.26 –
29 (2)	0.55 (0.06)	0.69 (0.30)	1.09 (0.04)	0.18 (0.08)	7.95 (0.24)	0.71 (0.09)
30 (2)	0.77 (0.06)	0.80 (0.18)	1.46 (0.14)	0.33 (0.04)	6.75 (0.08)	0.55 (0.04)
31 (1)	0.45 –	3.04 –	1.03 –	0.29 –	7.38 –	0.75 –
32 (1)	2.53 –	2.81 –	3.19 –	0.55 –	8.00 –	1.15 –
33 (1)	0.95 –	1.01 –	1.92 –	0.80 –	2.13 –	0.79 –
34 (1)	0.62 –	1.08 –	1.67 –	0.53 –	3.44 –	1.05 –
35 (1)	1.60 –	1.30 –	1.58 –	0.72 –	4.88 –	1.22 –
36 (3)	1.28 (0.14)	1.24 (0.16)	0.60 (0.13)	0.49 (0.09)	4.70 (2.44)	0.20 (0.17)
37 (2)	2.05 (0.69)	1.33 (0.26)	0.66 (0.18)	0.31 (0.04)	3.61 (1.15)	0.50 (0.07)
38 (1)	1.47 –	0.69 –	0.72 –	0.24 –	5.44 –	1.60 –
39 (4)	0.63 (0.11)	0.75 (0.18)	0.74 (0.18)	0.50 (0.13)	2.45 (1.06)	0.23 (0.10)
40 (4)	0.77 (0.21)	0.75 (0.18)	0.43 (0.08)	0.28 (0.08)	1.50 (0.87)	0.21 (0.02)
41 (144)	3.50 (1.42)	4.02 (1.21)	4.87 (1.53)	2.48 (1.38)	6.38 (1.51)	0.07 (0.10)

(continued)

CLASS (n)	DOMINANT FREQ (kHz) START	MIDDLE	END	MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)
42 (23)	0.69 (0.56)	1.08 (1.47)	5.70 (1.18)	0.17 (0.06)	7.16 (0.96)	0.15 (0.03)
43 (1)	2.11 -	0.55 -	4.01 -	0.23 -	7.43 -	0.14 -
44 (4)	0.72 (0.16)	0.62 (0.17)	3.14 (1.55)	0.29 (0.20)	4.36 (2.44)	0.11 (0.03)
45 (7)	2.39 (1.39)	2.39 (1.41)	2.38 (1.42)	1.32 (1.60)	5.03 (2.26)	0.02 (0.02)
46 (39)	0.61 (0.52)	0.41 (0.21)	0.41 (0.22)	0.18 (0.11)	3.22 (2.16)	0.04 (0.03)
47 (4)	1.55 (1.19)	1.52 (0.18)	1.12 (0.22)	0.64 (0.32)	3.07 (0.49)	0.11 (0.07)
48 (8)	1.42 (0.22)	0.83 (0.13)	1.31 (0.17)	0.58 (0.20)	2.48 (1.10)	0.12 (0.04)
49 (23)	1.88 (0.63)	1.81 (1.04)	1.85 (0.55)	0.50 (0.30)	5.40 (2.23)	0.19 (0.10)
50 (31)	0.68 (0.33)	1.31 (0.59)	1.73 (0.98)	0.29 (0.21)	4.32 (1.89)	0.18 (0.10)
51 (70)	1.34 (0.61)	0.48 (0.27)	1.43 (1.17)	0.18 (0.09)	4.21 (1.78)	0.22 (0.09)
52 (4)	1.46 (0.40)	0.47 (0.55)	0.75 (0.48)	0.25 (0.06)	7.63 (0.25)	0.41 (0.05)
53 (9)	1.40 (0.61)	1.66 (0.55)	1.83 (0.63)	0.81 (0.46)	3.35 (1.62)	0.17 (0.19)
54 (26)	1.54 (0.41)	1.47 (0.31)	1.00 (0.40)	0.17 (0.10)	4.13 (1.68)	0.26 (0.08)
55 (28)	0.49 (0.21)	0.41 (0.21)	0.39 (0.21)	0.22 (0.11)	1.48 (1.39)	0.08 (0.06)

(continued)

CLASS (n)	DOMINANT FREQ (kHz) START	MIDDLE	END	MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)
56 (25)	1.46 (0.78)	0.99 (0.33)	0.64 (0.31)	0.20 (0.09)	3.58 (1.71)	0.08 (0.04)
57 (162)	0.28 (0.16)	0.36 (0.22)	0.76 (0.45)	0.14 (0.04)	3.18 (1.85)	0.23 (0.10)
58 (4)	0.24 (0.05)	0.41 (0.10)	0.74 (0.39)	0.14 (0.03)	1.35 (0.60)	0.15 (0.04)
59 (3)	1.22 (0.24)	1.27 (0.87)	2.07 (0.31)	0.13 (0.01)	7.40 (0.60)	1.12 (0.13)
60 (1)	3.40 -	1.44 -	1.82 -	0.24 -	8.13 -	0.73 -
61 (201)	0.39 (0.38)	0.31 (0.28)	0.75 (0.52)	0.13 (0.01)	3.07 (1.74)	0.51 (0.11)
62 (2)	0.71 (0.11)	1.57 (0.23)	0.87 (0.02)	0.22 (0.13)	3.83 (0.33)	0.54 (0.15)
63 (3)	0.97 (0.46)	0.47 (0.01)	1.51 (0.39)	0.25 (0.11)	5.22 (1.90)	0.45 (0.13)
64 (2)	0.64 (0.23)	1.69 (0.22)	1.72 (0.27)	0.18 (0.06)	2.88 (0.18)	0.44 (0.04)
65 (1)	1.50 -	1.53 -	1.52 -	0.13 -	1.97 -	0.83 -
66 (3)	0.64 (0.03)	0.88 (0.11)	0.60 (0.09)	0.13 (0.01)	2.99 (1.29)	0.64 (0.09)
67 (4)	1.48 (0.11)	1.46 (0.09)	0.83 (0.88)	0.19 (0.08)	2.85 (0.92)	0.61 (0.04)
68 (1)	1.34 -	1.51 -	0.59 -	0.18 -	7.04 -	0.93 -
69 (29)	0.31 (0.17)	0.33 (0.38)	0.83 (0.79)	0.13 (0.01)	2.39 (1.52)	0.94 (0.13)

(continued)

CLASS (n)	DOMINANT FREQ (kHz) START	MIDDLE	END	MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)
70 (26)	0.56 (0.52)	0.53 (0.40)	0.54 (0.44)	0.13 (0.02)	3.63 (2.17)	3.32 (2.15)
71 (2)	0.99 (0.37)	0.59 (0.16)	1.02 (0.84)	0.23 (0.01)	2.05 (0.13)	1.55 (0.13)
72 (1)	0.13 -	0.13 -	0.54 -	0.13 -	2.91 -	2.57 -
73 (2)	0.18 (0.01)	0.21 (0.08)	0.21 (0.02)	0.15 (0.01)	0.33 (0.06)	1.05 (0.33)
74 (1)	0.72 -	0.17 -	0.12 -	0.13 -	2.01 -	1.36 -
75 (2)	0.39 (0.06)	0.71 (0.03)	0.54 (0.01)	0.13 (0.01)	2.92 (2.05)	0.49 (0.14)
76 (4)	0.54 (0.16)	0.09 (0.10)	0.49 (0.26)	0.12 (0.00)	2.89 (0.93)	0.62 (0.02)
77 (2)	2.40 (2.40)	0.00 (0.00)	2.10 (1.27)	0.13 (0.00)	7.19 (0.64)	0.33 (0.01)
78 (1)	1.68 -	0.22 -	1.50 -	0.12 -	3.94 -	0.78 -
79 (7)	1.46 (0.62)	0.06 (0.16)	0.27 (0.20)	0.13 (0.01)	3.33 (1.75)	0.46 (0.08)
80 (4)	0.93 (0.53)	0.10 (0.12)	0.50 (0.30)	0.13 (0.01)	4.25 (2.44)	0.57 (0.20)
81 (5)	1.80 (0.47)	1.21 (0.18)	1.55 (0.48)	0.60 (0.32)	5.09 (2.07)	0.79 (0.23)
82 (20)	1.06 (0.65)	0.94 (0.42)	0.96 (0.51)	0.15 (0.05)	4.96 (1.66)	1.34 (0.17)
83 (23)	0.89 (0.45)	0.47 (0.31)	0.52 (0.33)	0.13 (0.01)	3.41 (1.24)	0.88 (0.14)

(continued)

CLASS (n)	DOMINANT FREQ (kHz)			MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)
	START	MIDDLE	END			
84 (5)	1.14 (0.22)	1.01 (0.16)	1.86 (0.92)	0.17 (0.07)	3.77 (0.28)	0.90 (0.16)
85 (1)	0.94 -	1.67 -	1.72 -	0.29 -	2.62 -	1.59 -
86 (14)	1.82 (0.74)	0.89 (0.35)	1.55 (1.23)	0.20 (0.07)	6.66 (1.64)	2.38 (0.70)
87 (4)	1.72 (0.92)	1.35 (0.14)	1.25 (0.34)	0.47 (0.24)	4.73 (2.21)	3.65 (1.36)
88 (2)	3.06 (0.32)	1.37 (0.45)	0.73 (0.25)	0.62 (0.35)	4.71 (0.21)	0.38 (0.12)
89 (1)	0.65 -	0.61 -	0.66 -	0.44 -	0.96 -	1.00 -
90 (2)	1.80 (0.16)	1.83 (0.18)	0.69 (0.18)	0.52 (0.19)	3.84 (0.28)	1.03 (0.00)
91 (1)	1.40 -	5.28 -	0.61 -	0.41 -	3.66 -	1.06 -
92 (1)	1.18 -	1.35 -	0.92 -	0.24 -	2.13 -	3.32 -
93 (3)	1.29 (0.48)	0.95 (0.74)	0.60 (0.65)	0.13 (0.01)	6.39 (2.37)	2.03 (0.17)
94 (1)	1.57 -	1.09 -	2.32 -	0.35 -	3.73 -	0.41 -
95 (1)	0.82 -	0.65 -	1.03 -	0.56 -	6.64 -	1.26 -
96 (1)	2.05 -	1.22 -	1.92 -	0.22 -	3.97 -	2.11 -
97 (1)	1.19 -	3.98 -	2.94 -	0.12 -	7.73 -	5.97 -

(continued)

CLASS (n)	DOMINANT FREQ (kHz) START	MIDDLE	END	MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)
98 (10)	1.19 (0.21)	1.42 (0.23)	1.34 (0.26)	0.54 (0.18)	3.20 (0.62)	1.49 (0.25)
99 (2)	1.09 (0.36)	0.24 (0.01)	0.25 (0.08)	0.13 (0.00)	2.19 (0.30)	0.72 (0.31)
100 (4)	1.11 (1.16)	1.86 (1.23)	2.35 (0.82)	0.13 (0.00)	6.61 (1.27)	2.88 (1.35)
101 (2)	2.76 (0.28)	2.28 (0.30)	3.44 (0.21)	0.13 (0.00)	6.98 (0.76)	1.11 (0.40)
102 (2)	2.28 (0.26)	2.22 (0.18)	3.48 (0.08)	0.23 (0.01)	6.60 (0.30)	1.54 (0.10)
103 (22)	3.06 (1.70)	2.66 (1.37)	2.79 (1.53)	1.05 (0.60)	6.29 (1.77)	0.20 (0.08)
104 (1)	3.37 -	3.25 -	3.35 -	0.47 -	6.26 -	0.15 -
105 (1)	0.74 -	1.09 -	1.05 -	0.39 -	3.82 -	0.21 -
106 (1)	2.32 -	2.63 -	2.26 -	0.13 -	5.82 -	0.18 -
107 (1)	0.79 -	2.69 -	2.86 -	0.36 -	7.93 -	0.67 -
108 (1)	1.10 -	2.11 -	0.65 -	0.39 -	7.12 -	0.51 -
109 (3)	0.96 (0.55)	0.39 (0.17)	0.41 (0.17)	0.19 (0.05)	3.04 (2.54)	0.32 (0.10)
110 (1)	2.03 -	0.59 -	0.67 -	0.30 -	2.95 -	0.92 -
111 (1)	0.91 -	0.61 -	0.85 -	0.22 -	1.76 -	0.78 -

(continued)

CLASS (n)	DOMINANT FREQ (kHz) START	MIDDLE	END	MIN. FREQ. (kHz)	MAX. FREQ. (kHz)	DURATION (sec)
112 (2)	3.83 (0.51)	0.43 (0.04)	0.46 (0.06)	0.16 (0.06)	7.56 (0.69)	0.48 (0.13)
113 (1)	0.74 -	3.07 -	4.66 -	0.33 -	7.35 -	1.08 -
114 (2)	3.95 (2.26)	2.56 (0.70)	1.66 (0.40)	0.83 (0.50)	7.81 (0.10)	0.37 (0.13)
115 (1)	2.88 -	3.42 -	1.34 -	0.85 -	5.34 -	0.67 -