



Songs of Humpback whales (*Megaptera novaeangliae*): Described during winter mating season on a subarctic feeding ground in northeast Iceland

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Abstract

Humpback whale (*Megaptera novaeangliae*) songs were first described and characterized by Payne and McVay in 1971. The elaborate vocal display of song is still not fully understood, but it likely represents an important behaviour in mating and sexual selection. Humpback whales are a migratory species known to produce long, stereotyped, complex songs in breeding grounds during the winter time. However, more studies are detecting songs outside of the usual tropical warm breeding areas, in migration routes as well as in higher-latitude feeding grounds.

The study area, Skjálfandi Bay in northeast Iceland ($66^{\circ}07'N$, $17^{\circ}32'W$), is an established high latitude feeding ground for humpback whales during the summer. Former cetacean acoustic monitoring studies from 2008 to 2009 in this location, indicated that humpback whale song vocalizations were present in multiple 1 minute recording sound files. The present study supports and markedly expands on the previous acoustic findings from this location. It demonstrates and describes extensive song occurrence in winter months that were not previously recorded.

Long-term acoustic recordings were made in Skjálfandi Bay from 26 January – 12 March, 2011, using a bottom-moored Ecological Acoustic Recorder (EAR). The EAR was programmed to record in 10 minute cycles, every 5 minutes at a sampling rate of 16 kHz. The prevalence of songs by multiple individuals confirmed that at least part of the population remained in the productive waters throughout winter, and possibly year-round. The songs from this high latitude feeding ground also demonstrated a level of structure and pattern characteristic of songs described from mating grounds. The results had 19 phrase type classifications and displayed a predictable sequence from the cyclic patterns in the song recordings. Furthermore, peak song occurrence timing coincided with the peak timing of seasonal hormonal activity in sexually active humpback whales during breeding season in the Northern hemisphere. The findings demonstrate that this complex mating ground behaviour is in sync with breeding and conception time. Therefore, these data support that mating behaviour is not restricted to tropical breeding grounds. It further suggests that humpback whales may have the ability to mate and participate in breeding activity while remaining in Iceland's subarctic waters. The behavioural flexibility shown from this study recognizes the northeast coast of Iceland as an important year-round habitat for humpback whales.

Útdráttur

Söng hnúfubaksins (*Megaptera novaeangliea*) var fyrst lýst af Payne og McVay árið 1971. Tilgangur þessarar einstöku samskiptahegðunar hefur ekki fyllilega verið skýrður þó svo nýjustu kenningar telji að söngurinn þjóni mikilvægum tilgangi á æxlunartímanum. Hnúfubakurinn er fardýr, en þessa flóknu söngva er helst að heyra á trópískum æxlunarstöðvum þeirra að vetri til. Þó hafa sífellt fleiri rannsóknir leitt það í ljós að söngvarnir eru einnig sungnir utan hefðbundinna æxlunarstöðva, á farleiðum og á fæðustöðvum hvalanna á norðlægum breiddargráðum.

Rannsóknasvæðið, Skjálfandi flói við norðausturland ($66^{\circ}07'N$, $17^{\circ}32'W$), er mikilvæg fæðustöð hnúfubaka að sumri til. Fyrri rannsóknir, sem gerðar voru í flóanum frá 2008 til 2009, sýndu fram á sönghljóðbrot frá hnúfubökum í Skjálfanda flóa að vetri til í fjölda 1-mínútna neðansjávarupptökum. Rannsókn þessarar ritgerðar styður við þessar fyrri uppgötvanir og bætir jafnframt við umtalsverðri viðbótar þekkingu á sönghegðun hnúfubaka í Skjálfanda flóa. Rannsóknin sýnir fram á og lýsir viðamiklum söngvum hnúfubaksins að vetri til, jafnframt náðust upptökur yfir þá vetrarmánuði sem enging gögn voru til frá áður.

Neðansjávarhljóðupptökutækjum var komið fyrir á botni Skjálfanda flóa á tímabilinu 26. janúar – 12. mars 2011. Hljóðupptökutækin kallas *Ecological Acoustic Recorders* (EARs) eða „Eyr“ og geta tekið upp hljóð í langan tíma í senn. Eyrn voru stillt á 10 mínútna upptöku á 5 mínútna fresti yfir allt rannsóknartímabilið á 16 kílóriða sýnatökutíðni. Söngvarnir voru ákaflega tíðir yfir allt rannsóknartímabilið og voru söngvararnir oftast fleiri en einn í hverri upptöku. Því benda upptökurnar til þess að ákveðinn hópur hnúfubaka haldi til á næringarauðugri breiddargráðum yfir veturinn og jafnvel allan ársins hring. Söngvarnir í Skjálfanda flóa höfðu nauðalíka uppbyggingu og skipulag og þeir söngvar sem vel hafa verið rannsakaðir á hefðbundnum trópískum æxlunarstöðvum. Í rannsókninni voru greind 19 ólík erindi, þ.e. hljóðbútar með taktföstum tónum, sem byggðu upp söngva þessa tímabils í fyrirsjáanlegri runu. Enn fremur var söngvirknin í hámarki á þeim tíma sem frjósemi hnúfubaka er talin vera í hámarki á norðurhveli jarðar. Því benda niðurstöður rannsóknarinnar til þess að um æxlunartengda hegðun sé að ræða sem eykst til muna þegar líkur á æxlunarárangri aukast. Af því má ætla að æxlunarhegðun hnúfubaksins sé ekki einskorðuð við hefðbundnar æxlunarstöðvar og að hvalirnir, sem dvelja veturlangt við Íslandsstrendur, geti gert tilraunir til mökunar. Þessi sveigjanlega tímgunarhegðun hnúfubaksins bendir til þess að norðausturströnd Íslands sé mikilvægt búsvæði hnúfubaka allan ársins hring.

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*“My soul is full of longing for the secrets of the sea, and the heart of the great ocean sends
a thrilling pulse through me.”*

- Henry Wadsworth Longfellow

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1 Introduction

The humpback whale (*Megaptera novaeangliae*) is a medium sized baleen whale of the Balaenopteridae (rorqual) family (Johnson and Wolman 1984, Reeves and Smith 2002). This species is characterized by their very long pectoral flippers, which are almost one-third of the total body length, unique patterned underside flukes, and complex acoustic displays of ‘song’ (Schevill and Backus 1960, Johnson and Wolman 1984). Humpback whales have an average measured length of 15.6 metres, (17 to 18.5 metres in Iceland), and weigh approximately 34 metric tonnes (Johnson and Wolman 1984, WDC Iceland). A feature unique to the North Atlantic humpback whales is that they have white upper side flippers, whereas individuals from the Pacific have entirely black flippers (Chittleborough 1965). Humpback whales are regarded as one of the best-studied baleen whale species, yet much information is still being learned for these wide ranging cetaceans.

1.1 Distribution and Migration

Humpback whales can be found distributed in all ocean basins of the world (Johnson and Wolman 1984, Rice 1998,). Three reproductively and geographically isolated populations are recognized. Two major populations are found in the Northern Hemisphere; the North Atlantic and North Pacific populations, and one major population in the Southern Hemisphere, sub-categorized into six sub-populations or ‘stocks’ (Mackintosh 1965, Baker *et al.* 1993, Palsbøll *et al.* 1995, Rice 1998). The total abundance in the North Atlantic humpback whale population is estimated by Smith *et al.* (1999) to be approximately 10,600 individuals from 1992-1993 and more recent studies find that these populations should be increasing (Punt *et al.* 2006). However, a recent publication based on nuclear gene diversity by Ruegg *et al.* (2013) estimates a long-term population size of the North Atlantic humpback whales to be approximately 112,000 individuals (95% CI 45,000 – 235,000) which is almost 2 – 3 folds higher than the estimates based on Smith *et al.* (1999) catch data methods. These discrepancies show a large uncertainty for modelling humpback whale population growth and estimating population size over time. Recently estimated population numbers of humpback whales by Paxton *et al.* (2009) in Iceland showed 10,521 individuals (95% CI 3,716 - 24,636). Pike *et al.* (2009) found a population estimate of 11,572 ((95% CI 4,502 - 23,807) for their study around Icelandic waters and corrected for previous estimate biases. For northeast Iceland and its adjacent waters, estimates by Øien (2009) found an abundance of approximately 3,200 individuals (95% CI 1,140 – 9,260). In any case, recent studies show Icelandic waters are an important area for considerable numbers of summering humpback whales from the eastern North Atlantic population (Øien 2009, Paxton *et al.* 2009, Pike *et al.* 2009).

Like many baleen whale species, humpback whales have separate feeding and breeding grounds (Johnson and Wolman 1984). Figure 1.1 shows the different wintering and summering grounds inhabited by humpback whales from all around the world. They are known for making some of the longest recorded annual migrations (of up to 8000 km) from

high-latitude productive feeding areas to low-latitude tropical waters for breeding and calving (Stone *et al.* 1990, Kennedy *et al.* 2014). In the North Atlantic population, humpback whales are found migrating to and feeding in five main feeding areas: off the Gulf of Maine, eastern Canada (Newfoundland, Labrador, and the Gulf of St. Lawrence), West Greenland, Iceland and the Barents Sea of Northern Norway (Katona and Beard 1990, Stevick *et al.* 1998, Stevick *et al.* 2006, Kennedy *et al.* 2014). Individuals display a high degree of site fidelity, returning regularly to areas characterized by maternally directed behaviour (Palsbøll *et al.* 1995). The minimal exchanges observed between feeding areas has even lead to evolutionary differences of mitochondrial genetic markers between the differing groups (Palsbøll *et al.* 1995, Larsen *et al.* 1996).

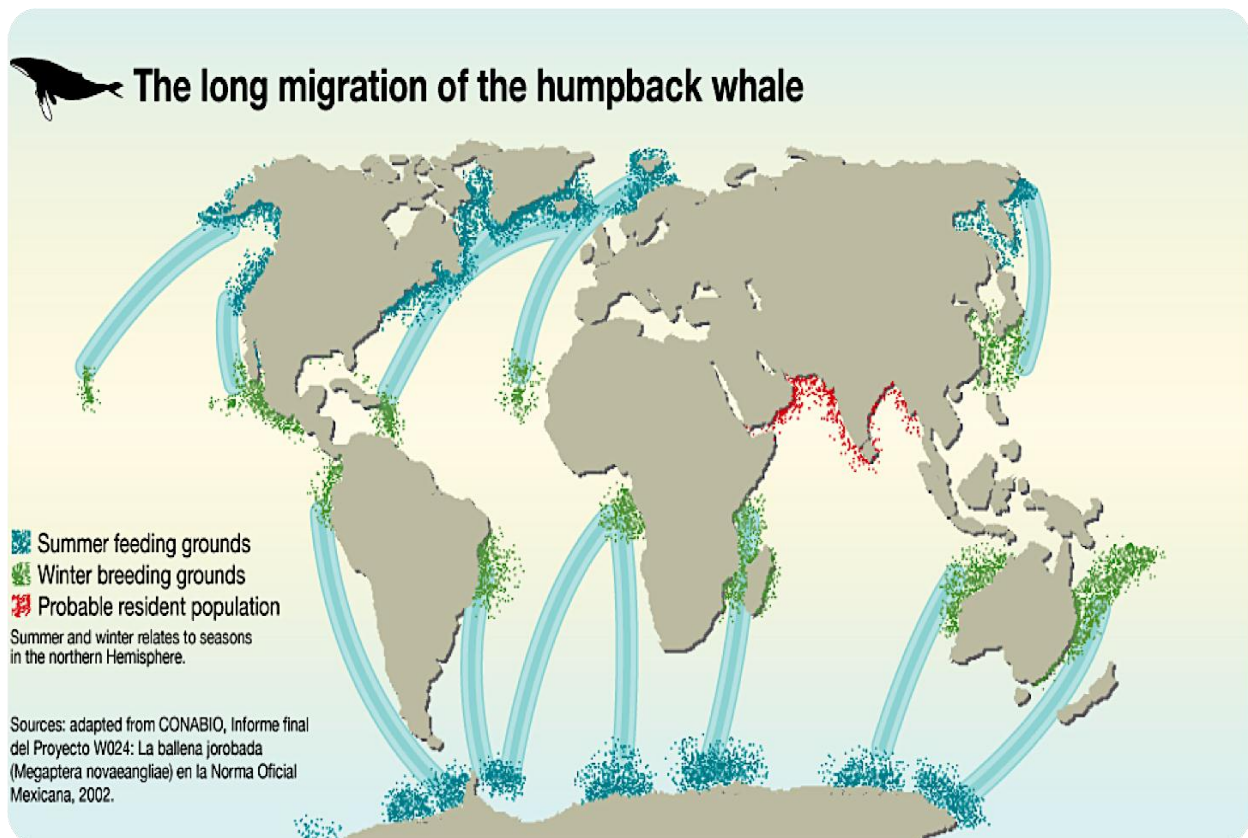


Figure 1.1. Migration routes of humpback whale populations distributed around the world. Dense blue coloured clusters indicate summer feeding grounds, and green coloured clusters indicate winter breeding grounds. The light blue paths in between show common migration routes taken between summer and winter breeding grounds. Figure by Riccardo Pravettoni, UNEP/GRID-Arendal, Living Planet.

Individuals from all the North Atlantic feeding grounds can be found to congregate in two common breeding areas: around the Antillean chain of the West Indies or around the Cape Verde Islands off West Africa (Hazevoet and Wenzel 2000, Stevick *et al.* 2003 and 2006, Wenzel *et al.* 2009 Kennedy *et al.* 2014). The Silver-Navidad-Mouchoir banks area off the northern coast of Dominican Republic (West Indies) is regarded as one of the largest breeding aggregation grounds for humpback whales (Whitehead and Moore 1982, Smith *et al.* 1999, Kennedy *et al.* 2014). Individual humpback whales from Icelandic feeding

grounds have been identified in both breeding sites, with verified genetic and photo identifications from Silver Bank and the Cape Verde Islands (Larsen *et al.* 1996, Jann *et al.* 2003, Stevick *et al.* 2003, Wenzel *et al.* 2009). Humpback whales are recorded leaving tropical breeding grounds in early spring, heading north towards high-latitude feeding grounds in Icelandic and Norwegian waters (Stevick *et al.* 2006, Kennedy *et al.* 2013).

1.1.1 Prey Species

Principle prey species for humpback whales are not yet fully understood in Icelandic waters. Studies on individual humpback whale distribution and on other baleen whales prey species in this area indicate that humpback whales feed primarily on euphausiid crustaceans and capelin (*Mallotus villosus*) (Sigurjónsson 1995, Stefánsson *et al.* 1997, Víkingsson 2004, Stevick *et al.* 2006). It is also suggested that the observed distribution patterns in humpback whales may in fact be influenced by a shift in prey abundance, initially feeding in euphausiid rich areas then switching to primarily feeding on capelin as the prey availability changes with mesoscale oceanographic features (Stevick *et al.* 2006, Smith and Pike 2009).

1.2 Reproduction

Based on historical whaling records, humpback whale males and females are considered to reach sexual maturity at 5 to 7 years of age (Chittleborough 1958). Physical changes during the fall and winter mating period include heightened hormonal levels for both males and females (Chittleborough 1958). Increase in testes size along with an increase in spermatogenesis rates occur in males and changes in ovulatory activity affect females (Chittleborough 1958, 1965). This time period signifies that much of their behaviour and energy is directed towards breeding and mating behaviour (Chittleborough 1958, Nishiwaki 1959). However, the act of mating has still not yet been witnessed (Pack *et al.* 2002).

Females have a gestation period of 12 months and the calf will usually stay with its mother for a year before separating (Tyack and Whitehead 1983, Clapham 2000). Therefore, females produce a single calf on average, every 2 to 3 years (Chittleborough 1958, Baker *et al.* 1987, Barlow and Clapham 1997). Male behaviour is also affected during this time period where individuals adopt different social roles and behavioural strategies for mating (Herman and Antinofa 1977, Tyack 1981, Tyack and Whitehead 1983, Tyack 1983, Clapham *et al.* 1992, Parsons *et al.* 2008).

1.3 Acoustic Behaviour

One of the most well studied behaviours of humpback whales during mating season is their vocalization and complex singing behaviour (Darling *et al.* 2012, Cholewiak *et al.* 2013). Humpback whales are known to produce some of the most diverse acoustic signals, both in the form of social sounds and in their complex songs (Payne and McVay 1971, Stimpert *et al.* 2007, Mercado *et al.* 2010, Stimpert *et al.* 2011). Social and feeding calls do not have the repetitive structure and pattern of a song and are produced by both females and males

(Silber 1986, Stimpert *et al.* 2007, Dunlop *et al.* 2008). On the contrary, singing has only been demonstrated by male individuals. Primary function of singing still remains unresolved and scientifically debated since its first discovery in the year of 1952 (Payne and McVay 1971, Parsons *et al.* 2008). It is highly likely that songs serve more than one function in the mating and communication system, both as an inter- and intra-sexual display for attracting female mates, and also as a competitive behaviour for establishing male dominance or lekking behaviour in their mating grounds (Tyack 1981, Tyack 1983, Tyack and Whitehead 1983, Darling and Berube 2001, Clark and Clapham 2004, Smith *et al.* 2008, Herman *et al.* 2013).

Humpback whale songs were first described by Payne and McVay (1971). Their leading study recognized a significant connection between the observed hierarchical structure of humpback whale song to the structure and pattern of bird song. Payne and McVay (1971) followed Broughton's (1963) definition of song, where "...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," was used to develop the terminology still applied by researchers for present day studies of humpback whale song. Figure 1.2 provides a visual breakdown representation of the humpback whale song structure as described by Payne and McVay (1971) and Guinee and Payne (1988). Although there are variations and inconsistencies between literature studies of humpback whale song description, the essential foundation still remains based on the originally proposed criteria by Payne and McVay. Cholewiak *et al.* (2013) recently discussed classification issues deviating between authors and provided an informative review and standard criteria based on Payne and McVay's original methods for consistent analytical approaches to song classification.

Figure 1.2. Humpback whale song hierarchy delineation. The ‘unit’ is the shortest, most basic element in the song, which are combined to form ‘sub-phrases’ and ‘phrases’, which are repeated in succession to form ‘themes’ that when sung continuously, reprise the formation of a ‘song session’. Duration times are only rough indicators given for this specific song example from Hawaii, figure by Guinee and Payne (1988).

1.3.2 Acoustic properties of song

Acoustic characteristics of humpback whale songs are repetitive, high intensity vocal signals sung in frequency ranges from low to mid-range between 30 Hz – 8 kHz, and at source levels between 151 and 173 dB re 1 μ Pa at 1m (Cerchio *et al.* 2001, Mercado *et al.* 2003, Au *et al.* 2006). Studies also find that sound pressure levels of songs increase between mid-February and mid-March (Au *et al.* 2000). Spectral peak frequencies are detected between approximately 315 Hz and 630 Hz (Au *et al.* 2000). Higher-frequency harmonics have also been recorded sometimes beyond 24 kHz (Au *et al.* 2006). These signals appear to mainly function as short-ranged communications (tens of kilometres) since they would not propagate as well as lower frequency (<100 Hz) sounds after attenuation and propagation loss through the environment (Winn and Winn 1978, Mercado *et al.* 2003).

1.3.3 Song dialect and change

Humpback whale songs display a high degree of similarity within ocean basins and even more so when populations are within close proximity to each other. This indicates that the geographical distance between populations directly influences song sharing capabilities between individuals. Therefore, different degrees of song similarity can be found amongst differing populations (Payne *et al.* 1983, Helweg *et al.* 1990, Cerchio *et al.* 2001, Garland *et al.* 2013a). Fundamental song structure and framework generally remains the same; however, distinct differences can be found in acoustic components (ie. units, phrases and themes) of songs. These components differ in geographically distinct populations from the North Pacific, North Atlantic, South Pacific and South Indian Oceans (Winn *et al.* 1981, Payne *et al.* 1983, Cerchio *et al.* 2001). For example, studies of songs from Hawaii and Mexico populations demonstrated a higher degree of similarity between them than when compared to songs recorded from Japan (Helweg *et al.* 1990, 1998, Garland *et al.* 2013a). Vocal sharing and song exchange between humpback whales is assumed to occur by three modes of transmission (Payne and Guinee 1983): 1) movement of individuals from one breeding population to another between seasons, 2) within-season movement of individuals between two breeding populations, and 3) song exchange on a shared migration route summer feeding ground in higher latitudes. The transmissions lead to a dynamic and constantly evolving formation of new songs seasonally and annually throughout any given population (Payne *et al.* 1983, Payne and Payne 1985, Cato 1991, Eriksen *et al.* 2005). Sharing and learning of songs demonstrate that cultural transmission and vocal learning occurs within and across regions between humpback whale conspecifics (Garland *et al.* 2013b). It is proposed that the novelty in hearing new songs stimulates song change and copying amongst individuals (Noad *et al.* 2000). Noad *et al.* (2000) demonstrated how an entire population of humpback whales in Eastern Australia had unexpectedly learned and replaced their own song with song from the neighboring Western Australian population within a very short time period of two years.

Songs are most commonly detected during mating season on low-latitude tropical breeding grounds. However, singing is also recorded during ‘shoulder-season’ or ‘off-season’ from spring, summer and autumn months, which are at the beginning and end of mating season (Mattila *et al.* 1987, McSweeney *et al.* 1989, Clark and Clapham 2004, Stimpert *et al.* 2012). Humpback whales are often recorded producing song vocalizations while traveling

on migration routes between feeding and breeding grounds (Clapham and Mattila 1990, Norris *et al.* 1999, Charif *et al.* 2001, Noad and Cato 2007).

Songs reported from higher latitude feeding areas during off-season and over short time periods included findings from the North Atlantic (Mattila *et al.* 1987, Clark and Clapham 2004), North Pacific (McSweeney *et al.* 1989), and off the Western Antarctic Peninsula (Stimpert *et al.* 2012). An exception is Vu *et al.* (2012), where they described continuous singing in a Northwest Atlantic feeding ground in almost every month of the year, with peak song detections during the shoulder season months. The most recent discovery of humpback whale singing in a high-latitude, subarctic feeding ground is by Magnúsdóttir *et al.* (2014) from Iceland's northern feeding grounds, with peak recordings of song units detected during 2008 and 2009's winter mating season (December to February). Here, in this present thesis study, new data and research provides the first detailed description and characterization of humpback whale song from Iceland's subarctic feeding ground.

1.4 Project Aim and Objectives

The objectives of this Master's research and thesis is to provide a greater understanding of humpback whale songs recorded from an Icelandic subarctic feeding ground by: 1) comprehensively describing and characterizing the structure and pattern of humpback whale songs recorded in an established, northeast Iceland, humpback whale feeding ground; 2) supporting and expanding the previous findings of humpback whale song signals recorded in 2008 – 2009 by Magnúsdóttir *et al.* (2014); 3) monitoring in months that were not previously studied using longer data recording methods in 2011 and; 4) thoroughly investigating the humpback whale song occurrence outside of their habitual breeding grounds during peak mating season.

2 Materials and Methods

2.1 Data Collection and Study Area

An Ecological Acoustic Recorder (EAR: Lammers *et al.* 2008; Figure 2.1) was deployed for long-term passive acoustic recording of humpback whales in the northeast coast of Iceland, between 26 January to 12 March, 2011.

The bottom-moored EAR is a microprocessor based autonomous recorder, with a response sensitivity of -193.5 dB that is flat (± 1.5 dB) from 1 Hz to 28 kHz. The EARs are designed to sample the ambient sound field on a pre-programmable duty cycle (Lammers *et al.* 2008).

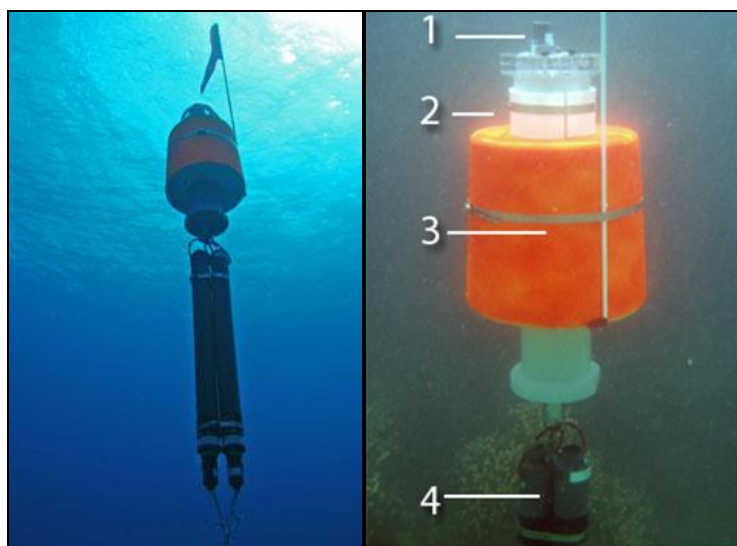


Figure 2.1. The left photo is of the Ecological Acoustic Recorder used for passive acoustic recording. The right photo shows the (1) aluminum housing, (2) syntactic foam collar, (3) and (4) two acoustic releases. Source: NOAA Fisheries, <http://www.pifsc.noaa.gov/cred/eartech.php>

The EAR was programmed to record for 10 minutes every 5 minute break, at a sampling rate of 16 kHz. The sampling rate was specifically set for targeting the vocalization range of humpback whales. Longer cycles were applied to record for longer sound files of humpback whale vocalizations. The detection range for a 1 kHz humpback whale acoustic signal are 12 km and 28 km based on the minimum 171 dB, and maximum 189 dB, source levels, which are similar to previous methods applied by Magnúsdóttir *et al.* (2014).

The EAR was deployed in Skjálfandi Bay on 26 February, 2011 in approximately 62 m depth near a slope named Fiskisker at 66°03'N, 17°40'W (Figure 2.2). The EAR was retrieved on 12 March, 2011 and re-deployed again at the same location in 2012 to further collect data in this area. However due to unknown equipment reasons, the EAR did not record any data from this period, thus only recordings from 2011 were analyzed.

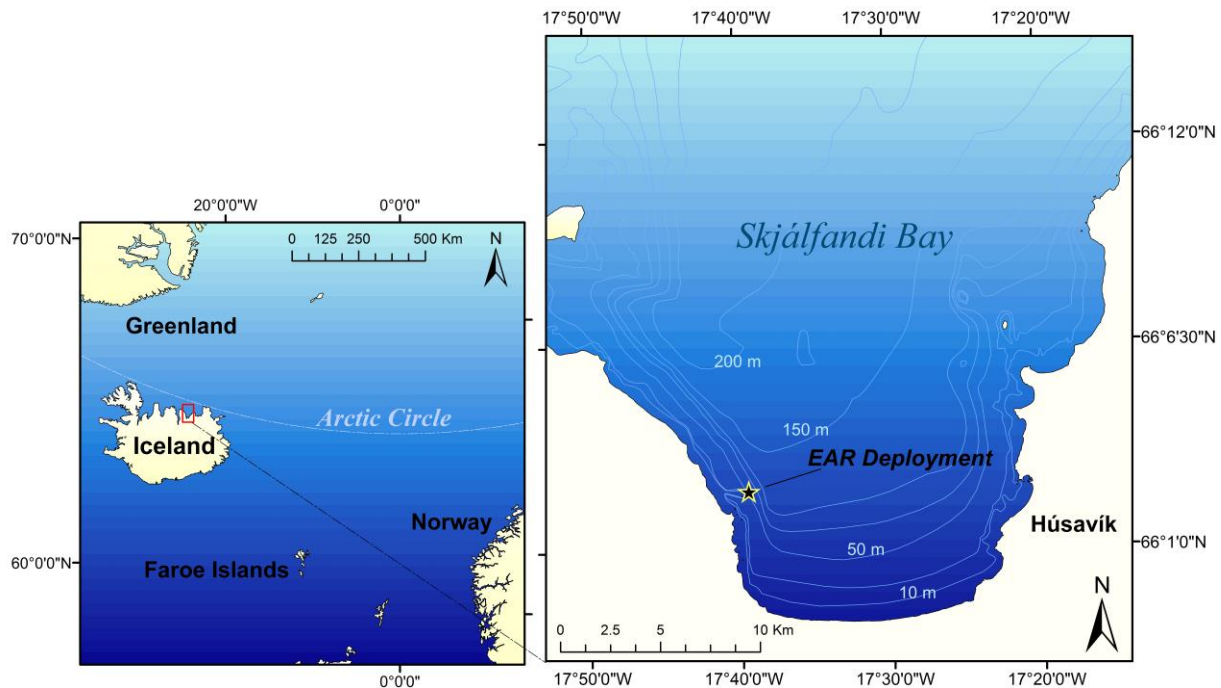


Figure 2.2. Study area in Skjálfandi Bay, NE Iceland. The star symbol (★) indicates the EAR deployment location at 66°03'N, 17°40'W. The map was created in ArcGIS, software. Source: 1) Hydrographic Department of the Icelandic Coast Guard, 2012, 2) National Land Survey of Iceland, 2012.

2.1.1 Northeast Iceland: Skjálfandi Bay

The study area for this research project is located in Skjálfandi Bay, northeast Iceland at 66°07'N, 17°32'W, near bordering the Arctic Circle (66.5622° N). The coastal waters in this area are more variable due to multiple influences and mixing from the Atlantic, Arctic and Polar oceans (Jonsson and Valdimarsson 2005). Increased nutrient and decreased salinity concentrations of Skjálfandi Bay are affected by two inflowing fresh water rivers: Laxá river from Lake Mývatn, and Skjálfandafljót river from Vatnajökull glacier (Gíslason 2004). The bay has a maximum depth reaching 220 m and is approximately 25 km wide (Gíslason 2004). Water temperature is approximately 2° Celsius in the winter time (Magnúsdóttir *et al.* 2014). Several monitoring studies showed that water temperatures are increasing over the past recent years of these North Atlantic waters (Astthorsson *et al.* 2007).

Capelin (*Mallotus villosus*) and cod (*Gadus morhua*) stocks are two of the most important species for this area and its ecosystem (Astthorsson *et al.* 2007). Icelandic waters are also an important habitat for some of the largest seabird populations in the northeast Atlantic

and to many species of cetaceans. Commonly observed species in this bay include, humpback whales (*Megaptera novaeangliae*), minke whales (*Balaenoptera acutorostrata*), white-beaked dolphins (*Lagenorhynchus albirostris*), harbour porpoises (*Phocoena phocoena*), blue whales (*Balaenoptera musculus*), fin whales (*Balaenoptera physalus*), bottlenose whales (*Hyperoodon ampullatus*), and killer whales (*Orcinus orca*). For the past several years, multiple whale watching companies operate from the nearby town of Húsavík, beginning in mid-April and ending in late October. However, in the winter, there is only an average of 3 hours daylight at this high latitude feeding ground. Therefore, darkness and unfavorable weather conditions restrict most cetacean observation and research for this area.

2.2 Song Definition

Humpback whale songs show a hierarchical structure where the individual shortest sound signals are termed ‘units’, which are grouped into ‘phrases’. The phrases are repeated to make up ‘themes’ that are sung in sequence to make a song. Song sessions are the result of multiple, repeated songs. A *subphrase* is defined as a sequence of one or more units that is sometimes repeated in a series or consecutive pattern (Payne *et al.* 1983, Cholewiak *et al.* 2013). Multiple *subphrases* are grouped or repeated into a *phrase* (Payne and Mcvay 1971).

Transition phrases are observed between two phrases and comprise of units from two different phrase types (Payne and McVay 1971, Cholewiak *et al.* 2013.). For example, using letters to indicate phrases, we observe the transition phrase ‘**ab**’:

aa aa **ab** bb bb

‘ab’ is the transitional phrase that includes a subphrase of ‘a’ and ‘b’. Therefore these are defined as transition phrases and not new phrases types.

2.3 Data Analyses

2.3.1 Preliminary Data Assessment

To analyze the entire wav file data sets retrieved, the program Ishmael 2.0 was used to detect acoustic signals of interest (Mellinger 2002, Mellinger *et al.* 2011). A frequency contour detection algorithm was used to search for tonal signals frequencies ranging from 100 to 1000 Hz. Detection thresholds were set to 0.25 seconds (FFT 0.2048 s., 75% overlap, Hamming).

Log files were created to show the number of signal detections identified per wav file and matched to the date and time of the files. These numbers were used for further selection of files for analyses. Generally, files with greater than 100 logged signals detected, but less than 300 detections were selected and manually analyzed. Files with more than 150 detections usually indicated multiple singers ‘chorusing’, meaning that multiple whales were singing at the same time, but not necessarily synchronized, where spectrograms

displayed overlapping units in parts of the file, and wav files with 300 or more detections usually indicated multiple singers chorusing throughout the entire file.

Logged files showing signal detections were displayed as spectrograms (FFT size: 1024, Hanning window, 85% overlap) using the BatSound analysis PC Software program (Peterson Elektronik A.B. 1996). Visual and aural verifications were completed for all files to select for high quality sound files with high signal to noise ratios.

Spectrograms with humpback whale signal detections were separated into five different categories: very poor, poor, medium, good and excellent based on the clarity of spectrograms and audibility of sound files. Excellent quality files were classified when all signal details were distinctly visible with high amplitude units and harmonics, as well as measurable clear phrases and good signal to noise ratio. Good files were classified when most signals of the file were clearly visible with few signal details faded out for a limited number of units, and duration was still measurable and identifiable. Medium quality files were defined as having units and phrases present, sometimes measurable but usually with lower amplitude and intensity. Poor files had units present that were too low in amplitude to measure. Very poor files had barely detectable units present. Files with overlapping signals from multiple individuals were noted but not included for further analysis.

Excellent sound files were identified from every day of the recording period. Four to six excellent files were selected per day depending on the number of detections shown from the log file. However, if one day had very limited numbers of excellent files available, good or medium files were also considered. Poor and very poor files were not used.

2.3.2 Song Characterization and Delineation

Unit, phrase and theme types were classified visually and aurally from spectrograms using BatSound. Duration measurements were determined using the measurement tool in BatSound. Figure 2.3 gives an example of a sample spectrogram file with the vertical **y**-axis representing frequencies up to 8 kHz, and the horizontal **x**-axis shows positive time given in seconds read from left to right up to a maximum of 600 seconds (10 minutes). As the wav files were only 10 minutes long due to data recording limitations, themes were only analyzed where possible since exact start and end of songs could not be analysed. A spectrogram catalogue was created and used for comparison to define units, phrases, themes and phrase transitions accordingly (delineation shown in Figure 2.3). These are shown in the Results section.

Units and phrases were delineated and characterized by analyzing the shape, signal frequency range and duration. The units and phrases were given alphabetical names, but are not related to the timing of occurrence. Longer phrase durations indicated higher numbers of unit repetition thus unit counts were not determined here. Phrase durations were measured using only excellent spectrogram files with greatest clarity and signal-to-noise ratio.

Multiple authors recognize phrase duration as being one of the most stable features in song, demonstrating that very little variation occurs within and between singers of the same

population (Frumhoff 1983, Payne *et al.* 1983, Cerchio *et al.* 2001, Cholewiak *et al.* 2013). Unstable theme orders can make it difficult to measure and compare ‘song length’, even when analyzing songs within the same region. This methodology can be inconsistent when multiple authors try to define the start and end of varying song sequences. As humpback whale songs are variable and continuously evolving, song durational analysis was advised against by Cholewiak *et al.* (2013). Cholewiak *et al.* (2013) recommended that maintaining a consistent phrase description and focus on the sequences of phrases, following established avian literature, be applied to humpback whale songs. For this thesis study, phrase delineation is the most effective and stable element for song structure analyses. The start and end of a song sequence was not necessarily required for structure delineations. Therefore, phrases were the primary elements considered in this comprehensive assessment.

Transitional phrases were chosen for analysis since they directly indicated the change and pattern found in the songs. The pattern could then be analyzed and described. Repeated, predictable patterns show the characteristics of humpback whale song. Cyclical pattern and song organization could further reveal any song patterns unique to this geographical area.

When possible, themes in this study would be categorized and measured. Full theme duration in this case would encompass the leading transitional phrase. Thus, in this example:

aaa aaa aab bbb bbb bbd ddd ddd

the Theme A sequence would include the first three underlined phrase sequences, and the second Theme B would follow as shown with the dotted underline, and so forth.

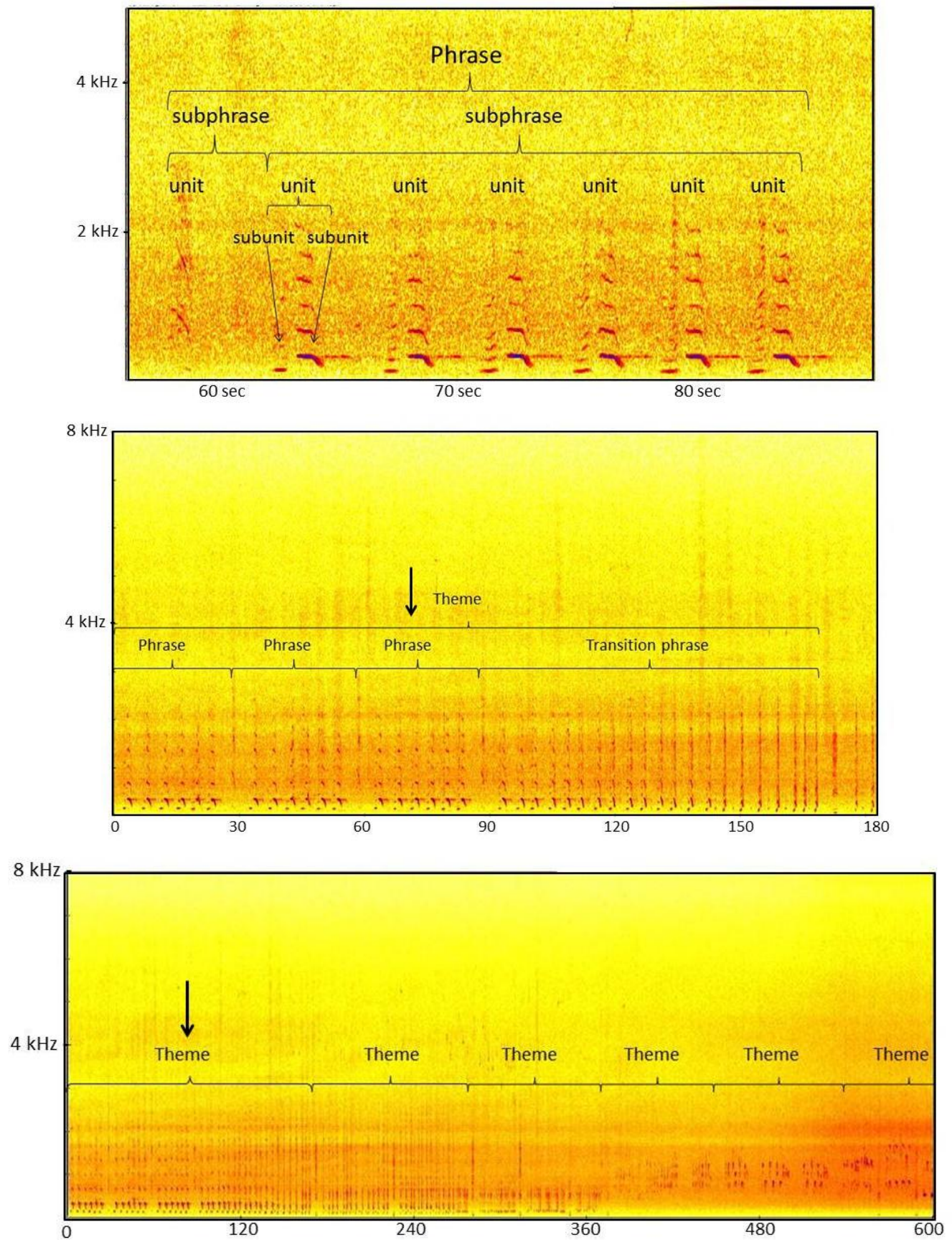


Figure 2.3. Spectrogram delineation example from 13 February, 2011. Black vertical arrows indicate the area of focus. The colors represent the relative amplitude, with red representing the highest energies, then in decreasing order of importance, orange to yellow to white areas with the least energy. The x-axis represents time (up to 600 seconds), and the y-axis represents the frequency (maximum of 8 kHz).

2.3.3 Statistical Analyses

The R program (free software: <http://www.r-project.org>) was used to perform all statistical analyses for this research. Packages applied included: cran, stats and pgirmess, in addition to any other particular listed packages below.

Comparison of Durations between different Phrase Types

The durations of each phrase type were compared between each other to disclose any differences amongst them (ie. Phrase a durations were compared to Phrase b durations). It was expected that greater differences indicated greater deviations from a given phrase type. Hypotheses were:

- H_0 : There are no differences between the different phrase type's durations
- H_1 : There are differences between the different phrase types's durations

Data were tested for normality using the Shapiro-Wilk normality test and Bartlett's test for homogeneity of the variance. To compare the temporal characteristics of song phrases, durations of all phrase types were compared between groups using the non-parametric Kruskal- Wallis test. The ANOVA test was applied to Phrase type datasets that satisfied all assumptions.

Comparison of Durations within the same Phrase Type

The durations within each phrase type were also compared to identify if there were any differences within the type. Phrase types with the highest frequency of occurrence (n values) were selected for analyses. (Phrase types: a, b, f, g, j, l, m, o and x). Within each phrase type, sample sizes were divided into three (as even as possible) groups for comparison. Phrase durations are regarded as the most stable element in a song, therefore it was expected that large durational differences would not occur within the same phrase types. Hypotheses were:

- H_0 : There are no durational differences within a phrase type's groups
- H_1 : There are durational differences within a phrase type's groups

Data were tested for normality using the Shapiro-Wilk normality test and Bartlett's test for homogeneity of the variance. To compare the temporal characteristics of song phrases, durations of all phrase types were compared within groups using the non-parametric Kruskal-Wallis test. The ANOVA test was applied to Phrase type datasets that satisfied all assumptions. Bonferroni correction was applied for obtaining the P values to eliminate bias in testing within the same dataset several times. The coefficient of variance was also calculated for each phrase type to express the ratio of the standard deviation (SD) to the mean. This represents the spreading compared to the average and is used for comparing different samples with different means (Fowler *et al.* 1998).

First-order Markovian Dependency Process for Sequential Pattern Analysis

Markov chain analysis distinguishes and identifies if sequences of events or behaviours are random by chance, or inherently contains a degree of temporal order; hence depending on the immediately preceding events. It is a suitable mathematical model used for describing sequential dependencies observed. In the first-order Markov process, probabilities of the different events depend only on the immediately preceding event, but not on earlier events (Lemon and Chatfield 1971, Dobson and Lemon 1979).

Transitional phrases were chosen for analysis in this thesis study since the transitional phrases directly indicated the change and pattern found in the recorded humpback whale songs. This pattern could then be characterized and described, since repeated, predictable patterns show organization and sequences of songs. Any cyclical patterns and song organization could further reveal song patterns unique to Iceland.

The phrase transition occurrences (n values) are ‘behaviour-based’ where a transition from one behaviour state to the next is observed (in this case the behaviour is a ‘phrase’). A transition matrix can be established to summarize the observed sequences of events. Since the study is interested in finding the *changes* and *transitions*, a phrase does not follow itself (ie. Phrase a cannot be followed by Phrase a, etc.). Therefore, the transition matrices are asymmetrical with frequencies of zero on the diagonal, and ‘true’ independence is not possible (as shown in the Results section). All variations of one phrase type were grouped together to form a simplified matrix for analyses (ie. where Phrase f includes both f and f2; or Phrase j includes j and jfast – shown in Results section). The observed transition frequencies were calculated using percentages of occurrence in Markov transition matrices. The numbers of transition types were calculated as percentages out of the total number of transition types observed.

The expected values for a chi-square test were calculated for the phrases using an iterative procedure, which estimated the expected values by a series of successive approximations until the values converged and became stable (values were determined using the R program). The complete results technique with the expected value tables is available in Appendix A. As an additional measure to account for large degrees of freedom used in the chi square test, a matrix using only the most frequent phrase transition occurrences with smaller degrees of freedom (df) were also analyzed. Detailed calculations for these additional matrices are available in the Appendix A.

Since ‘true’ independence is not possible, the hypothesis for testing ordered dependency is modified to recognize ‘quasi-independence’:

- H_0 : The order of the phrases are not quasi-dependent of each other
- H_1 : The order of the phrases are quasi-dependent of each other

Phrase transition figures were used to visually display transition occurrence and pattern. The R program with package: diagram was applied for creating transition figure.

Comparison of Durations between different Theme Types

The durations of themes were compared between 13 of the theme types to find if there were any differences between them. Only themes with frequencies >1 were analyzed. It was expected that greater differences in the theme durations would indicate greater deviations from a given theme type. The differences could also be used to compare with results from the phrase durational comparison analysis. Hypotheses were:

- H_0 : There are no differences between the different theme type's durations
- H_1 : There are differences between the different theme type's durations

Data were tested for normality using the Shapiro-Wilk normality test and Bartlett's test for homogeneity of the variance. To compare the temporal characteristics of song themes, durations of all theme types were compared between groups using the non-parametric Kruskal-Wallis test.

Comparison of Durations within different Theme Types

Comparison of durations within the same theme types were not completed using the Kruskal-Wallis tests. This was due to the limited sample size available for the different theme types as the sample sizes were too small for multiple group divisions needed for the applicable statistical test. However, coefficient of variances were calculated and analyzed for the themes. The coefficient of variance was applicable for representing the durational spreading in the themes when compared to the averages (the ratio of the standard deviation to the mean).

3 Results

3.1 Effort and Data Overview

The EAR at “Fiskisker” recorded for a period of 47 days (1 month and 17 days including the start and end dates). The first recording began on 25 January, 2011 at 22:00, and the last recording was completed on 12 March, 2011 at 16:00. A total of 4296, 10 minute wav files were collected and analyzed, where each day consisted of 96 recordings; except for the first day, which contained 8 wav files, and the last day with 65 wav files. Ishmael automatically detected humpback whale signals in 77.5% of all wav files.

Humpback whale signals were present every day with peak detections occurring from mid-to-late February with the highest detection numbers found on 16 February, 2011 (Figure 3.1). Multiple singers were commonly detected in the recording period. A total of 1026 files contained > 150 detections (~24%) per 10 minute spectrogram, and 213 files (~5%) contained more than 300 detections per 10 minute spectrogram. An example spectrogram showing multiple singers with overlapping phrases and units is shown in Figure 3.2. These multiple singer files were not used when the overlapping phrases were too obscured or difficult to differentiate start and end position.

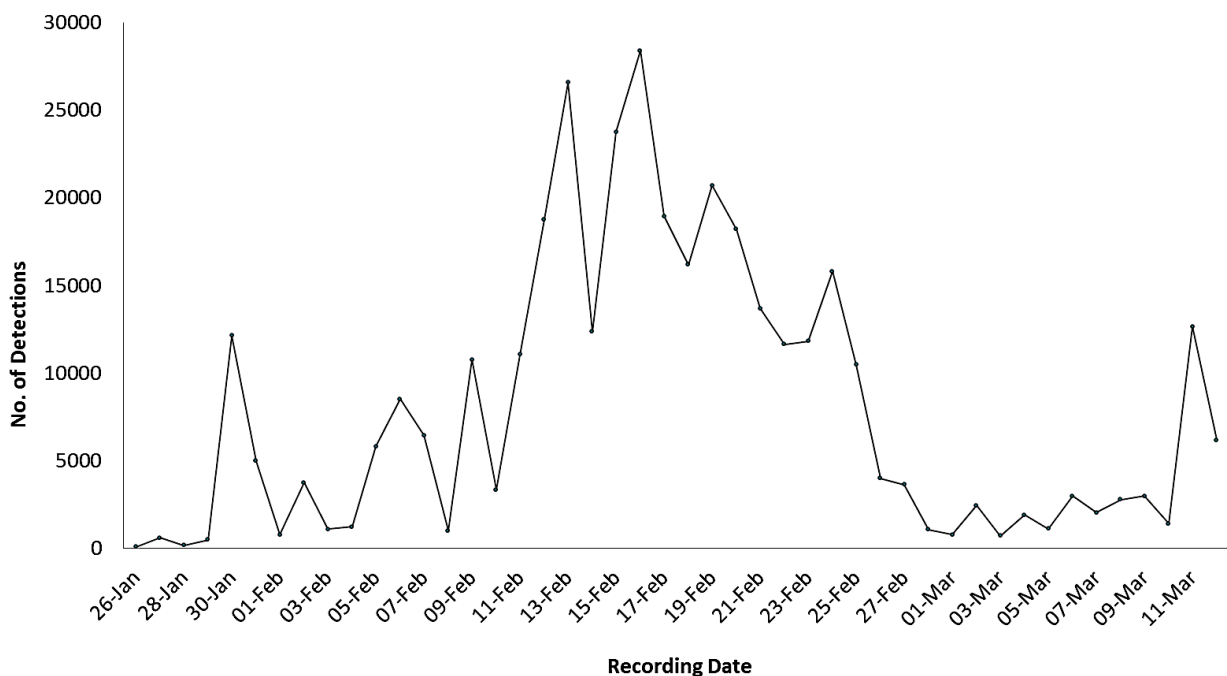


Figure 3.1. Number of automatic humpback whale signal detections recorded per day from 26 January to 12 March, 2011. Peak song signal detections occurred on 16 February, 2011.

A total of 151 high quality sound files with excellent signal-to-noise ratio were analyzed, totalling 1510 minutes (25 hours and 10 minutes). No sound files were analyzed on three days (27 February, 28 February, and 03 March, 2011) during the recording period. This was due to very low quality sound files and a low number of signal detections for these days. A table summary of all detection and sound file counts per day are available in the Appendix B.

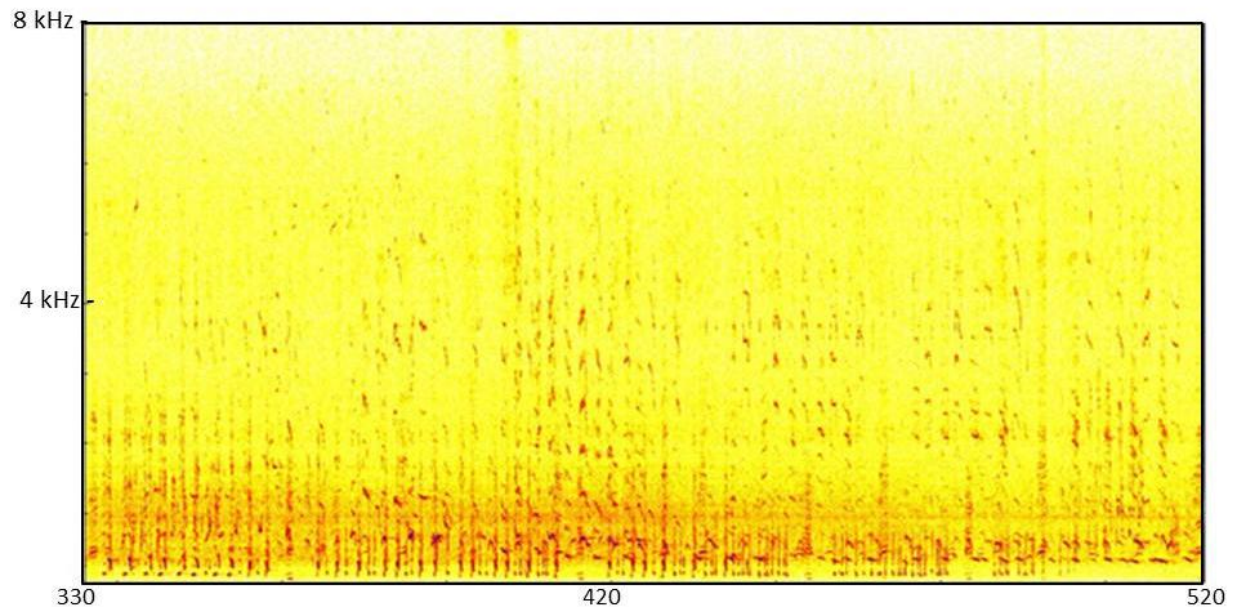


Figure 3.2. *Multiple singer spectrogram example. The spectrogram demonstrates overlapping units and phrases which were too difficult to differentiate between singers. FFT size: 1024, Hanning window, 85% overlap.*

3.2 Song Characteristics

3.2.1 Units

Twenty-four unit types were identified in 2011's winter recordings (Table 3.1). Eight of the unit types showed slight variations to an already identified unit and were sub-categorized instead of given a new unit name (these sub-categories are not bolded). The variations from the original 'parent type' involved slight differences in the structure, length of duration or frequency, without a consequent shift in the overall composition of the unit. These units were delineated as 'long', 'short', 'high', 'fast', or '2' (where the variation was observed in the second subunit). Units will be shown later per detailed phrase spectrograms (Section 3.2.2).

Unit type's z1 and z2 were unique as they were always observed as one singular unit between two pause intervals. These units were sung without repetition and followed by a pause before the start of a new unit. Unit z1 was first identified on 20 January, 2011

whereas Unit z2 was first identified on 05 February, 2011. Both unit types were never found to be sung in a phrase.

Table 3.1. *Twenty four unit types identified from 2011's winter recordings. Not bolded unit types are slight variations of their bolded 'parent type'.*

Unit Types		
Unit a	Unit g	Unit k
Unit a - long	Unit g - long	Unit l
Unit a - short	Unit g - short	Unit m
Unit b	Unit h	Unit n
Unit c	Unit i	Unit n2
Unit d	Unit j	Unit p
Unit f	Unit j- high	Unit z1
Unit f2	Unit j - fast	Unit z2

3.2.2 Phrases and Subphrases

A total of 19 phrase types (total n = 922) were identified and analyzed from 2011's winter recordings (Figures 3.3 - 3.8). The five most common phrases observed were Phrase a (n = 43), Phrase b (n = 260), Phrase f (n = 219), Phrase j (n = 166), and Phrase l (n = 58). A summary table for Phrases is shown in Table 3.2.

The Subphrase z1 and Subphrase z2 were only found to occur at the start of phrases (seen as a primary subphrase). Subphrase z1 and z2 consisted of the Unit z1 and Unit z2 respectively, followed by a pause interval before a new repetition of units (new subphrase) was sung. Together, these multi-subphrases composed a *phrase*. Subphrase z1 occurred more commonly than Subphrase z2 (n = 953; 73% and n = 353; 27%, respectively). Subphrase z1 (Figure 3.3-1) was characterized by Unit z1 as a low frequency harmonic 'groan' (0.44 kHz approximately 1.2 – 2 seconds long). Subphrase z1 was associated with almost all subphrases, as shown later in each phrase type description. Subphrase z2 was characterized by Unit z2 with a higher frequency 'scream' (~ 1 kHz harmonic downswept call approximately 0.7 – 1 second long). Subphrase z2 was most highly associated with Phrase b (> 82% of the time) and also sometimes with Subphrases a, f2 and k (Figure 3.4-7).

Table 3.2. Summary table showing calculations of each phrase type's occurrence (count), percentage, measured averages, maximum and minimum values, standard deviation and coefficient of variance.

<i>Phrase Type</i>	<i>Count (n)</i>	<i>Percent</i>	<i>Average Duration (sec)</i>	<i>Max</i>	<i>Min</i>	<i>Standard Deviation (SD)</i>	<i>Coefficient of Variance</i>
Phrase a	43	4.7	29.6	75.5	12.5	12.6	42.5
Phrase b	260	28.2	36.9	103.8	10.3	11.8	32.0
Phrase c	4	0.4	21.5	28.5	16.9	5.6	25.9
Phrase d	12	1.3	32.4	50.4	22.2	9.5	29.4
Phrase f	219	23.8	27.3	59.6	10.1	7.6	27.8
Phrase f2	3	0.3	29.8	40.9	19.3	10.8	36.3
Phrase g	40	4.3	17.4	29.6	13.9	2.9	16.8
Phrase i	2	0.2	19.9	21.6	18.1	2.5	12.5
Phrase j	166	18.0	26.6	43.4	16.1	5.3	19.8
Phrase jfast	6	0.7	19.8	27.8	15.7	4.3	21.9
Phrase k	6	0.7	28.7	34.3	24	4.4	15.2
Phrase l	58	6.3	22.3	37.1	13.6	5.2	23.1
Phrase m	26	2.8	20.1	34.1	14	6.0	30.0
Phrase n	8	0.9	25.9	31.2	18.2	5.0	19.2
Phrase o	30	3.3	24.7	54.1	16.2	6.9	27.9
Phrase o2	12	1.3	21.8	29	14.9	4.3	19.5
Phrase p	3	0.3	17.7	24.8	13.2	6.2	35.3
Phrase w	2	0.2	59.7	67	52.3	10.4	17.4
Phrase x	22	2.4	36.1	45.9	29	5.3	14.8
Total	922	-	27.3	-	-	-	-

Phrase a

A total of 43 Phrase a's were found throughout the period (5% of all phrases). Phrase a was composed of a primary subphrase (z1) and subphrase a - Figure 3.3-1. In some cases, Phrase a did not include a primary subphrase and only a subphrase a was recorded – Figure 3.3-2. The average duration of Phrase a was measured to be approximately 29.6 seconds (SD: 12.58). The phrases consisted of simple downswept 'moan' units (~ 1.0 second).

Phrase b

Phrase b was the most commonly identified phrase throughout the recording period (n = 260; 28.2%). It was composed mainly of primary subphrase z2 with subphrase b (subphrase z1 occurred <5%). In some instances, Phrase b did not include any primary subphrases. Phrase b had the longest maximum single phrase duration recorded at 103.8 seconds (SD: 11.81). Average durations were found to be approximately 36.9 seconds. This phrase as seen in Figure 3.3-2 was characterized by an initial simple and brief subunit followed by a high-to-low frequency contoured downswept unit (thus each unit consisted of 2 subunits).

Phrase c

This phrase was identified 4 times throughout the recording period (0.4%). It was composed of primary subphrase z1 and subphrase c (Figure 3.3-4). Average duration was measured at 21.5 seconds (SD: 5.56). Phrase c was characterized by a modulated unit (~1.0 second).

Phrase d

Phrase d was identified 12 times (1.3%) with an average duration of 32.4 seconds (SD: 9.51). It was composed of subphrase z1 and subphrase d (Figure 3.4-5). It was characterized by a fast harmonic, modulated-upswEEP unit, ending in a higher pitched frequency 'whup' sound.

Phrase f and Phrase f2

Phrase f was identified 219 times and was the second most recorded phrase type (23.8%). It had an average duration of 27.3 seconds (SD: 7.59) and was composed of primary subphrase z1 and subphrase f (Figure 3.4-6). This phrase looked similar to Phrase b, however it was characterized by a longer subunit (with longer pause space) followed by a high-to-low frequency contoured downswept unit with slight modulation. Each Unit f was also longer in duration and had a higher peak frequency than Phrase b.

Phrase f2 was similar to Phrase f except that the second subunit was much higher in frequency with a sharper downswept high-to-low frequency contour (Figure 3.4-7). This phrase variation was identified 3 times (0.3%) during the recording period and had an average duration of 29.8 seconds (SD: 10.81).

Phrase g

This phrase type was very distinct in comparison to other phrases due to its very low frequency sounding units and few repetitions per phrase. Phrase g consisted of the longest measured individual Units g (up to 5 seconds long in duration per unit), though had the shortest measured phrase durations. It was identified 40 times (4.3%) with an average duration of 17.4 seconds (SD: 2.92). It began with primary subphrase z1 and usually consisted of only 2-3 units per subphrase g (Figure 3.4-8). It was characterized by very low frequency sounding pulse-train ‘groan’ units.

Phrase i

Phrase i was one of the least frequently observed phrases, identified only 2 times (0.2%). It had an average duration recorded at approximately 20 seconds (SD: 2.47) and consisted of subphrase z1 and subphrase i with mid-to-high ranging frequency modulated units (Figure 3.5-9).

Phrase j and Phrase jfast

Phrase j was the third most frequent phrase type, recorded 166 times (18%) and had an average duration of 26.6 seconds (SD: 5.27). It was composed of the shortest measured units (approximately 0.12 seconds per unit), sung in quick multiple repetitions of short tonal upswing units (Figure 3.5-10).

Phrase jfast (Figure 3.5-11) had very fast repeating units with even shorter tonal upswing bursts recorded at an average duration of 19.8 seconds (SD: 4.32). This phrase variation type was identified 6 times (0.7%).

Phrase k

Phrase k was recorded 6 times (0.7%), with an average duration of 28.7 seconds (SD: 4.36). It was composed of a primary subphrase and subphrase k (Figure 3.5-12). This phrase was characterized by its repeating downswept calls which looked like a fragmented unit consisting of two separated, but continuous sub units. The first unit, a short, higher frequency subunit followed by a downsweeping contoured subunit.

Phrase l

This phrase type was observed 58 times (6.3%), and was one of the five most frequently observed phrases throughout the recording period. Phrase l had the highest peak frequency of all other measured phrases (up to approximately 3 kHz). It had an average duration of 22.3 seconds (SD: 5.15) and was composed of subphrase z1 followed by a subphrase of repeated high-pitched modulated ‘screams’ (Figure 3.6-13).

Phrase m

Phrase m was the first phrase identified with more than one unit type per subphrase repeating in a consecutive pattern. It was first recorded on 12 February, 2011 and characterized by Unit m and Unit n sung in succession (Figure 3.6-14). Phrase m was identified 26 times (2.8%) and had an average duration of 20.1 seconds (SD: 6.02). Sometimes Unit n was repeated more than once near the ending of the phrase.

Phrase n

This phrase was identified 8 times (0.9%) with an average duration of 26 seconds (SD: 4.97). It was composed of repeating high frequency modulated, Unit n (Figure 3.6-15). These units had a similar contoured shape like Phrase l; however, each unit was not as long in duration and had a lower peak frequency.

Phrase o and o2

Phrase o consisted of two unit types starting with Unit p and followed by Unit n in a consecutive pattern (Figure 3.7-16). It was recorded 30 times (3.3%) with an average duration of 24.7 seconds (SD: 6.90).

Phrase o2 was recorded 12 times (1.3%), had an average duration of 22 seconds (SD: 4.25) and began with the same Unit p but followed with a varied, higher frequency downswept modulated Unit n (Figure 3.7-17).

Phrase p

This phrase was identified 3 times (0.3%) throughout the recording period. Phrase p was characterized by Unit p repeated in sequence with an average duration of 17.7 seconds (SD: 6.24). The phrase was composed of a rounded contour modulated unit that can be seen in Figure 3.7-18.

Phrase w

Phrase w was only identified 2 times (0.2%) in the recording period (on 15 February and 11 March) with an average duration of 59.7 seconds (SD: 10.39). The two recordings showed longer durational measurements in comparison to other phrase types. It was characterized by subphrase z2 and Unit b and Unit j. These were sung in a distinct alternating pattern of Unit b followed by Unit j (Figure 3.7-19).

Phrase x

Phrase x was identified 22 times (2.4%) with an average duration of 36.1 seconds (SD: 5.33). It is characterized by subphrase z1 and Unit d and Unit j. These were sung in a repetitive pattern, in some phrases Unit d or Unit j were repeated more than once and ended the phrase with multiple repetitions of Unit j (Figure 3.8-20)

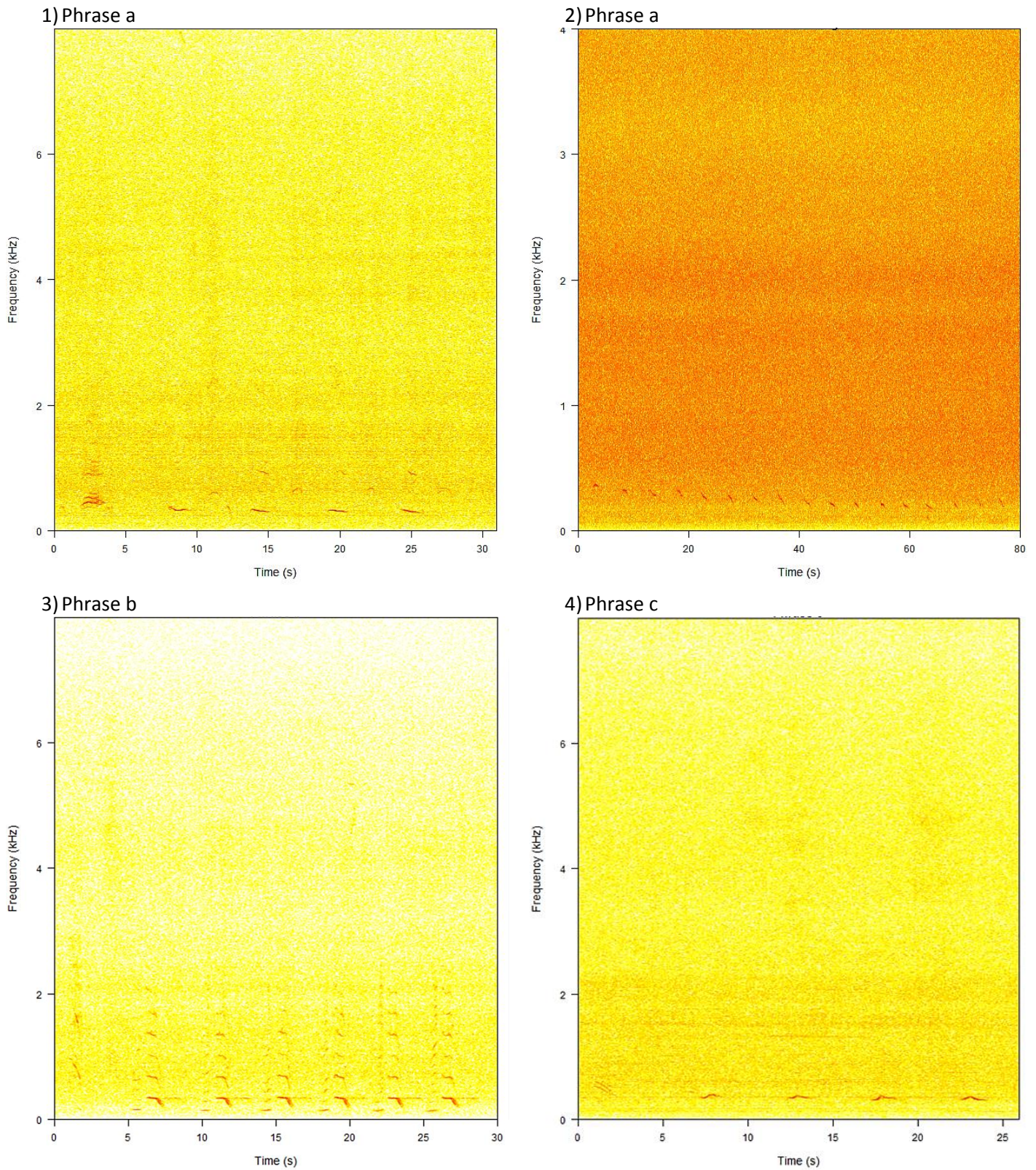


Figure 3.3. (1) Phrase a showing primary subphrase z1, and second subphrase a. Each unit type within the phrase is labeled with a unique given letter 'a' (2) Phrase a without a primary subphrase (only one subphrase type); note the different frequency scale of 4 kHz here (3) Phrase b composed of subphrase z2 and subphrase b. Subphrase b contains an initial simple, brief subunit followed by a high-to-low frequency contoured downswept unit (4) Phrase c consisting of two subphrases: subphrase z1 and subphrase c with modulated units. Spectrograms frequency scale reaches a maximum of 8 kHz. FFT size: 1024, Hanning window, 85% overlap.

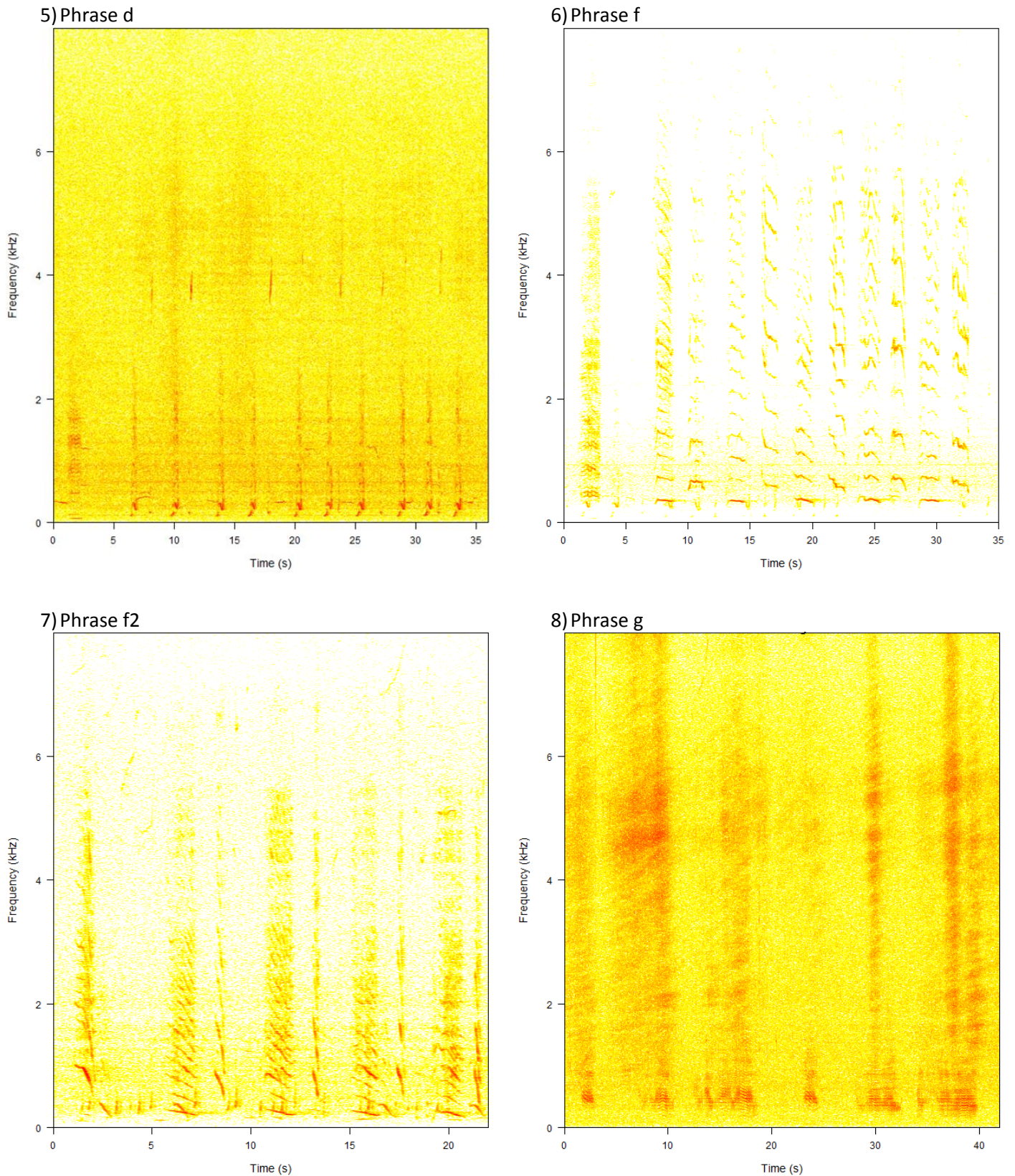


Figure 3.4. (5) Phrase *d* consisting of two subphrases, subphrase *z1* and subphrase *d* with fast modulated upswEEP units (6) Phrase *f* consisting of two subphrases, subphrase *z1* and subphrase *f* (7) Phrase *f2* with subphrase *z2* and subphrase *f2* characterized by the second sharper downswEEP subunit (8) Two phrases of Phrase *g*; each consisting of subphrase *z1* and subphrase *g* (two units). Spectrograms reach a maximum of 8 kHz. FFT size: 1024, Hanning window, 85% overlap.

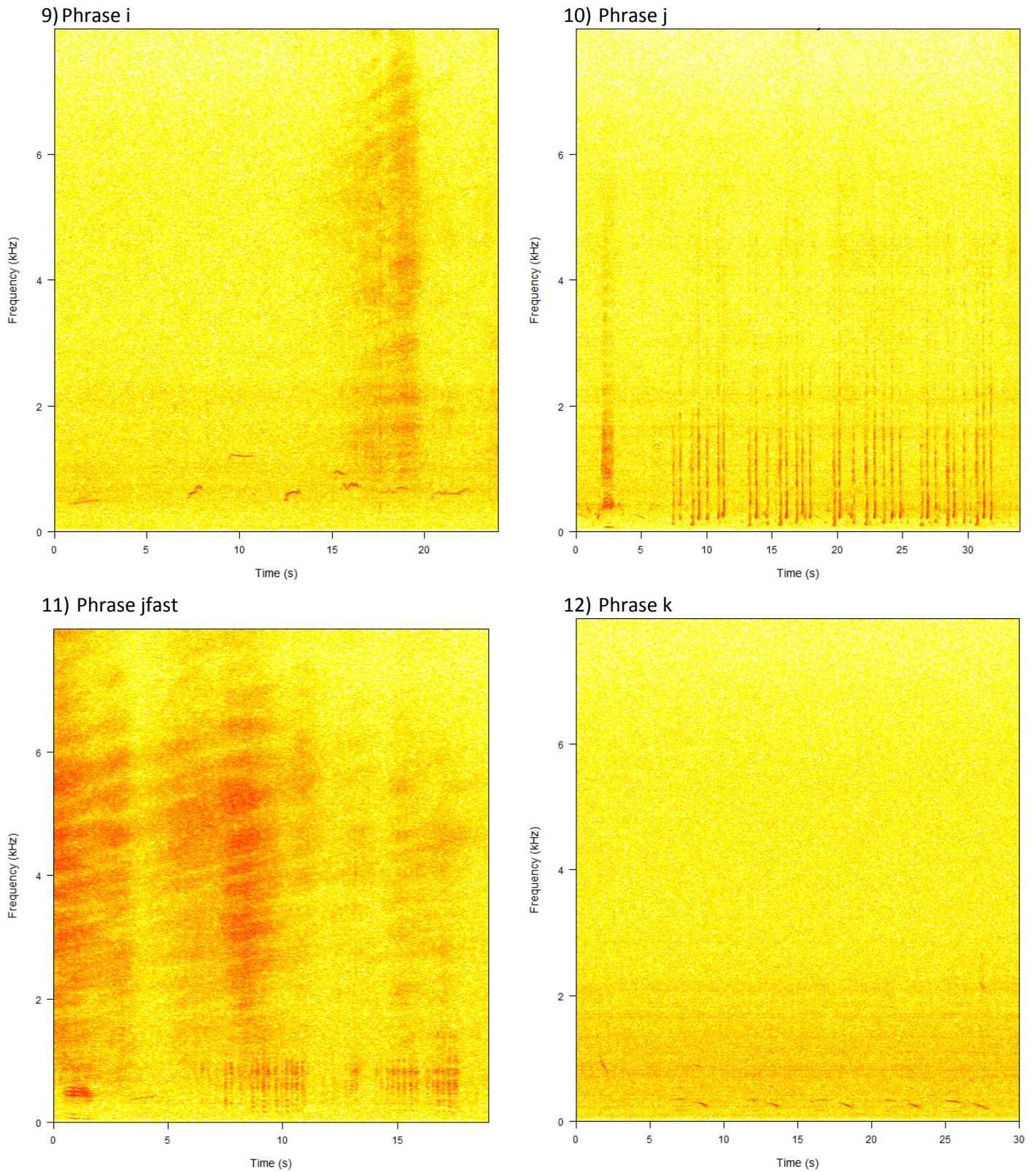
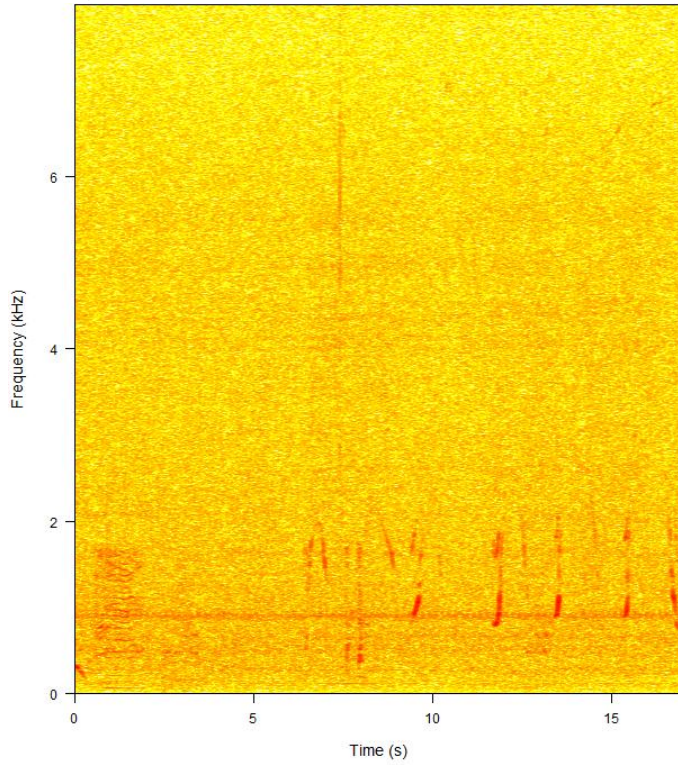
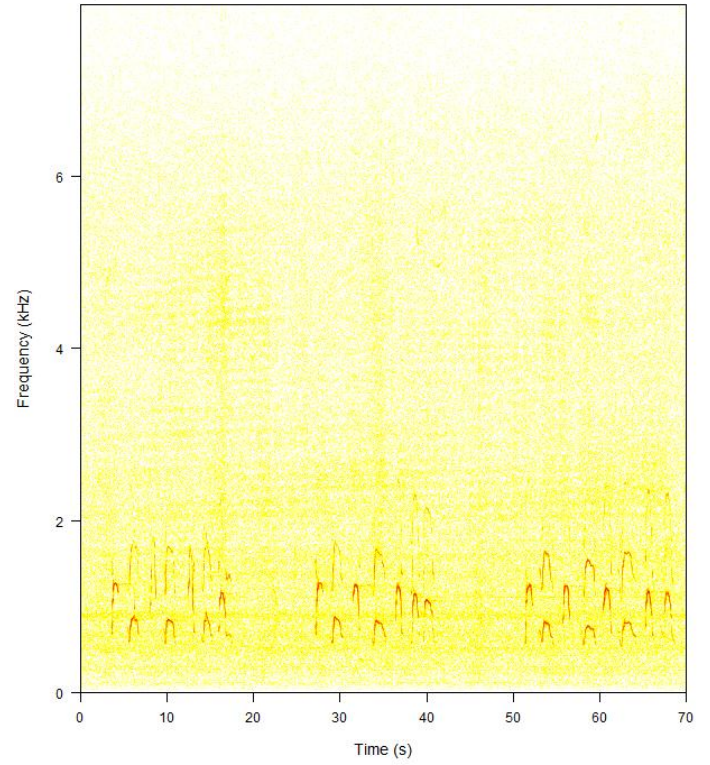


Figure 3.5. (9) Phrase i consisting of subphrase z1 and subphrase i (10) Phrase j consisting of subphrase z1 and multiple subphrases of j of the short tonal upsweep units (11) Phrase jfast showing multiple subphrases and shorter, faster repetitions of the tonal upsweep bursts (12) Phrase k consisting of subphrase z1 and subphrase k. Spectrograms reach a maximum of 8 kHz. FFT size: 1024, Hanning window, 85% overlap.

13) Phrase l



14) Phrase m



15) Phrase n

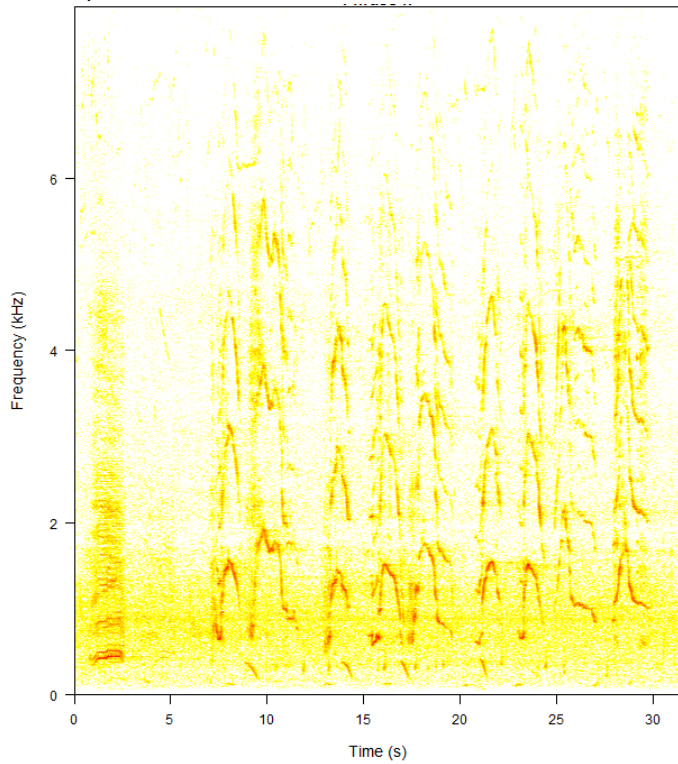
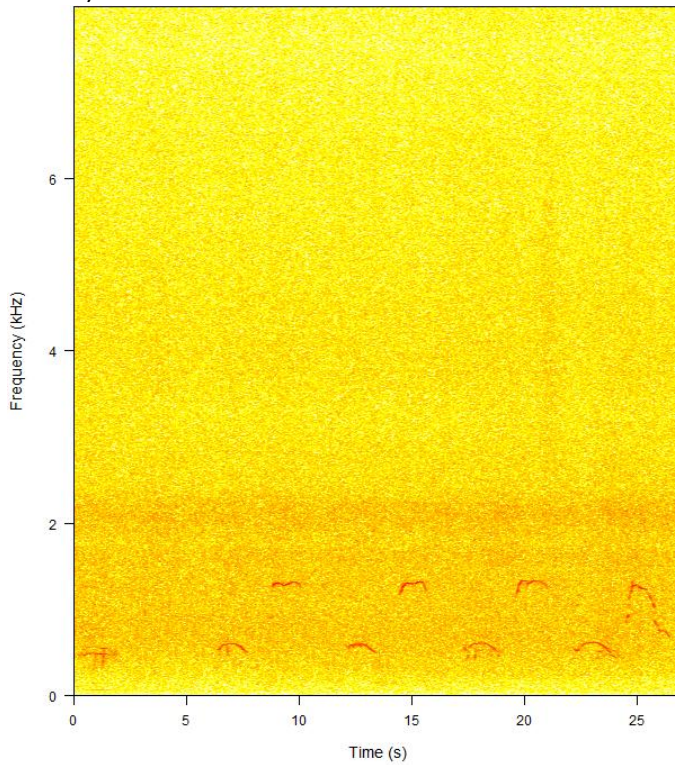
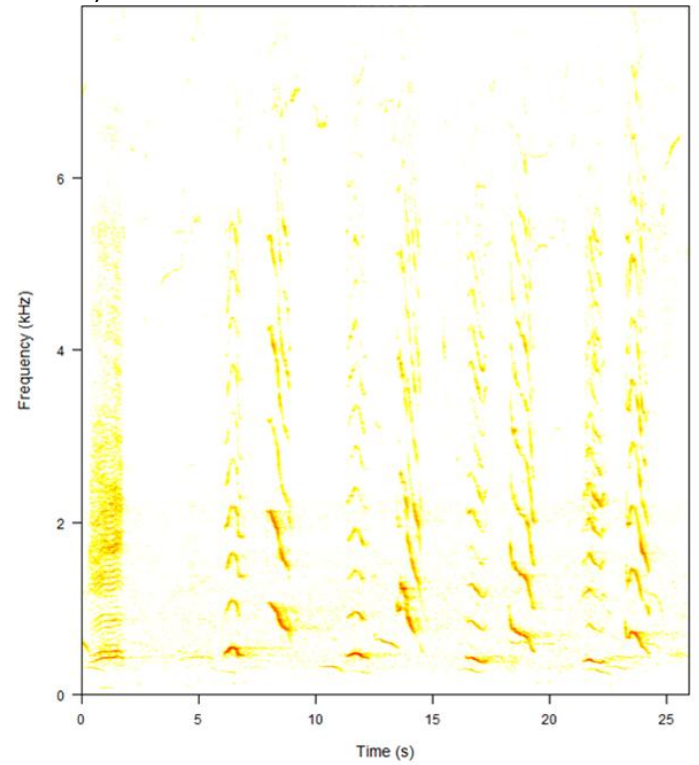


Figure 3.6. (13) Phrase l consisting of subphrase z1 and high frequency units from subphrase l (14) Phrase m showing units m and units n (15) Phrase n consisting of repeating n units and having units n repeated more than once near the ending. Spectrograms reach a maximum of 8 kHz. FFT size: 1024, Hanning window, 85% overlap.

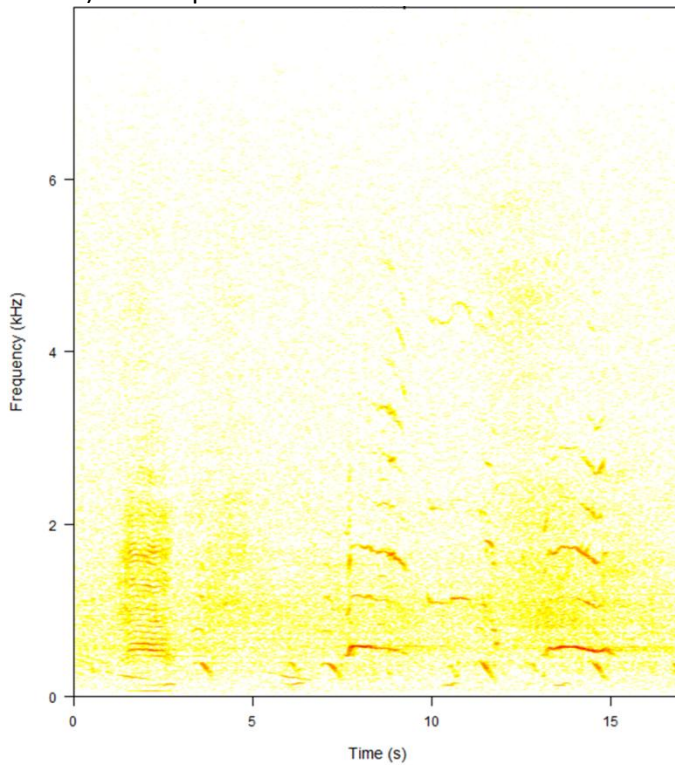
16) Phrase o



17) Phrase o2



18) Phrase p



19) Phrase w

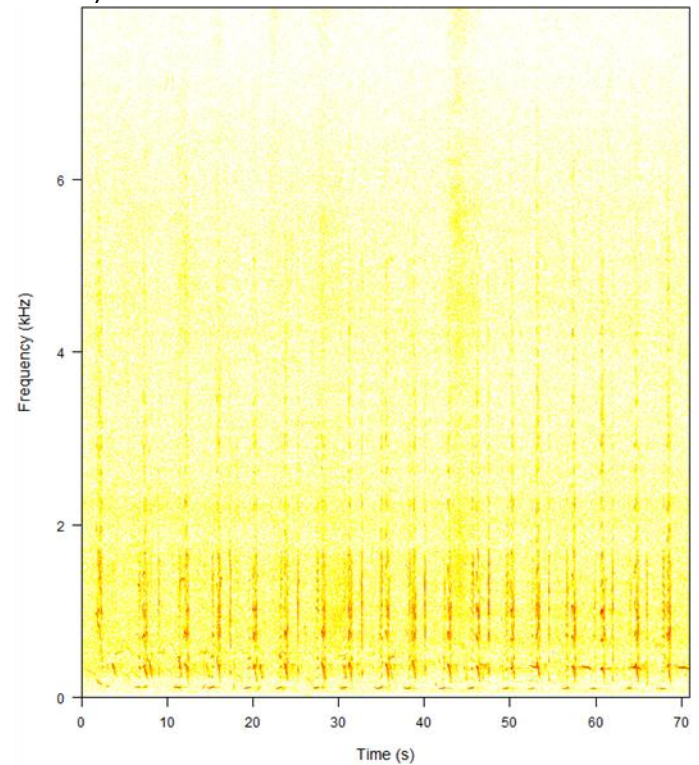


Figure 3.7. (16) Phrase o consisting of subphrase z1 and subphrase o with repeating units p and units n (17) Phrase o2 with units p and followed by a varied higher frequency downswept modulated n2 unit. (18) Phrase p consisting of subphrase z1 and subphrase p (19) Phrase w consisting of two subphrases: subphrase z2 and subphrase w with repeating Units b and Units j. Spectrograms reach a maximum of 8 kHz.

20) Phrase x

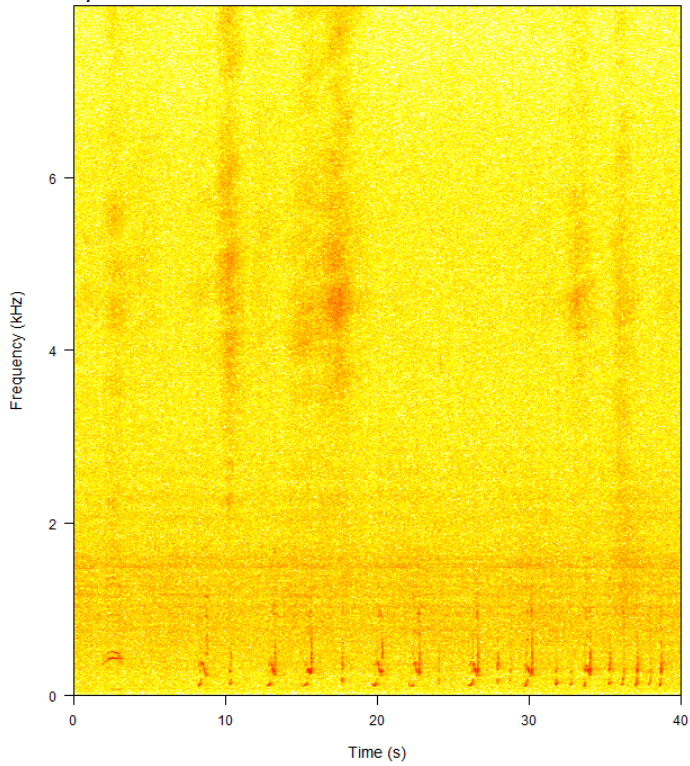


Figure 3.8. (20) Phrase *x* consisting of two subphrases, subphrase *z1* and subphrase *x* with repeating units *d* and units *j*. Spectrograms reach a maximum of 8 kHz. FFT size: 1024, Hanning window, 85% overlap.

3.2.3 Transition Phrases and First-order Markovian Dependency

The five most frequently observed transition phrases (greater than 10%) were Transition Phrases: a-b, b-d, d-j, j-l, and x-j (Table 3.3-1). Three different subphrase types were sometimes combined into a transition phrase between the previous and subsequent phrase types (Table 3.3-2).

Table 3.3. 1) Table of transition phrase types with count (n) and percentage (out of the total). 2) Table of transition phrases types with 3 subphrases

1)

Transition Phrase Types (2 subphrases)	Count (n)	Percent (%)
Transition Phrase a's	51	-
a to b	44	10.6
a to d	1	0.2
a to f	1	0.2
a to k	5	1.2
Transition Phrase b's	104	-
b to d	76	18.3
b to f	3	0.7
b to k	2	0.5
b to x	23	5.5
Transition Phrase c's	6	-
c to a	4	1
c to f	2	0.5
Transition Phrase d's	60	-
d to j	42	10.1
d to x	18	4.3

I) *Table continued*

Transition Phrase Types (2 subphrases)	Count (n)	Percent (%)
Transition Phrase f's	43	-
f to a	31	7.5
f to b	11	2.6
f to c	1	0.2
Transition Phrase g's	1	-
g to k	1	0.2
Transition Phrase j's	45	-
j to g	1	0.2
j to l	44	10.6
Transition Phrase k's	11	-
k to b	11	2.6
Transition Phrase l's	21	-
l to f	1	0.2
l to m	10	2.4
l to o	9	2.2
l to p	1	0.2
Transition Phrase m's	8	-
m to f	1	0.2
m to n	1	0.2
m to o	6	1.4
Transition Phrase n's	2	-

I) *Table continued*

Transition Phrase Types (2 subphrases)	Count (n)	Percent (%)
n to o	2	0.5
Transition Phrase o's	13	-
o to f	13	3.1
Transition Phrase p's	4	-
p to f	4	1
Transition Phrase w's	3	-
w to x	3	0.7
Transition Phrase x's	44	-
X to J	44	10.6
Total	416	-

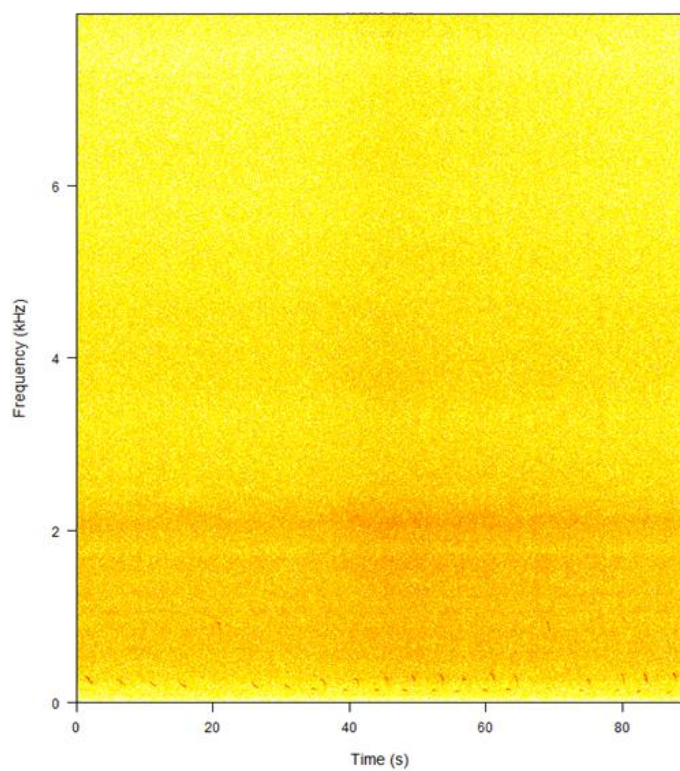
2)

Transition Phrase Types (3 subphrases)	Count (n)	Percent (%)
Phrase b-d-j	2	8.3
Phrase b-d-x	10	41.7
Phrase b-x-j	1	4.2
Phrase c-a-b	1	4.2
Phrase c-f-a	1	4.2
Phrase d-x-j	2	8.3
Phrase d-x-j	1	4.2
Phrase f-a-b	4	16.7
Phrase f-b-d	1	4.2
Phrase l-o-o2	1	4.2
Total	24	-

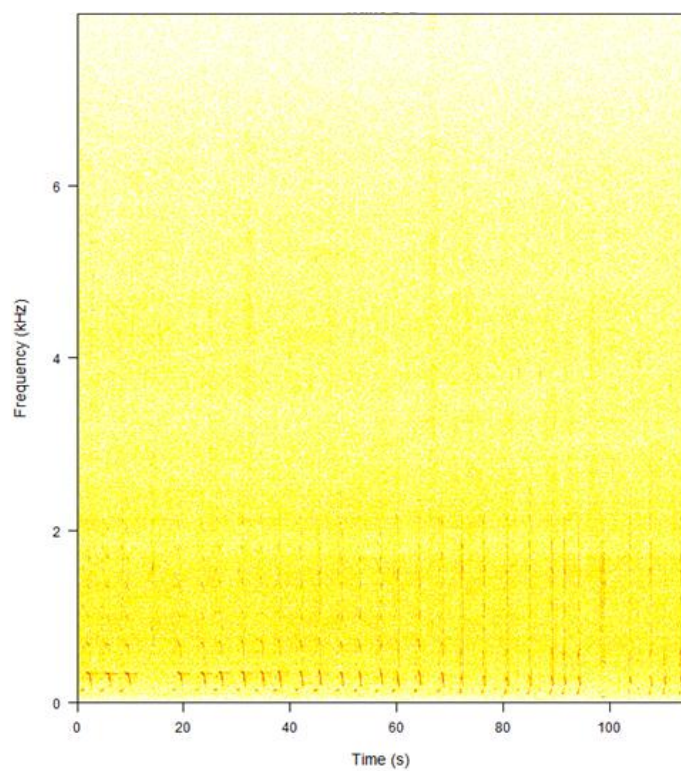
Detailed durations are not included in this section as these transition phrase results focus on pattern and sequence analyses. However, transitional phrase durations can be found in the summary table of the Appendix E.

Spectrogram examples are provided in Figures 3.9 to show the five most frequently observed transition phrase types and an example of a transition phrase type with 3 subphrases.

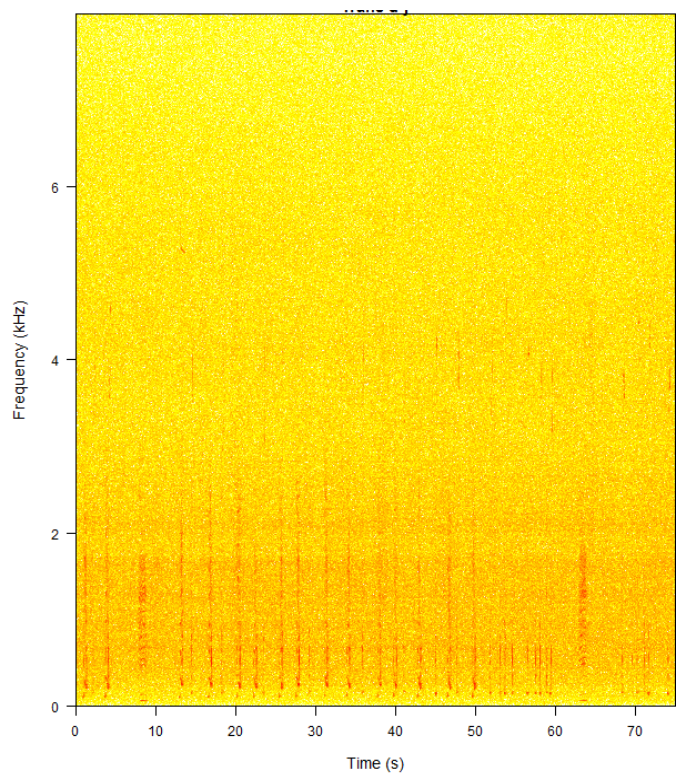
1) Transition a-b



2) Transition b-d



3) Transition d-j



3) Transition x-j

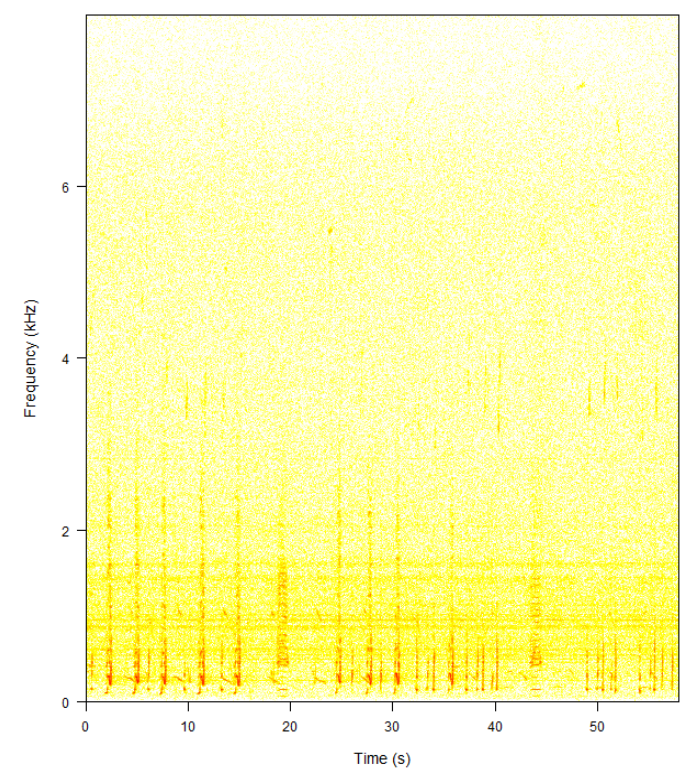


Figure 3.9. Spectrograms of the transition phrase (1) Transition phrase a-b, (2) Transition phrase b-d and (3) Transition phrase d-j.

4) Transition f-a-b

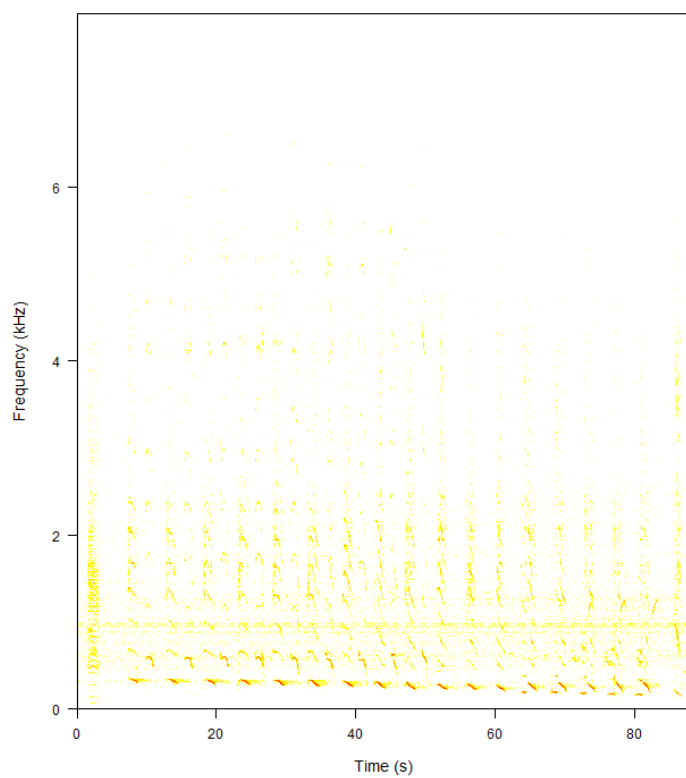


Figure 3.10. (4) Spectrogram of the Transition phrase *f-a-b*. This transition is composed of 3 subphrases.

First-Order Markovian Dependency

A chi-square test was applied to analyze First-order Markovian dependency in 15 of the most frequently occurring phrase transitions. Results indicated that sequential dependency was highly significant ($P < 0.001$). Therefore H_0 is rejected as the order of the phrase transitions are sequentially quasi-dependent of each other. The calculated χ^2 value ($\chi^2 = 2095.2$) greatly exceeded the critical value ($\chi^2_{0.001; 181} = 245.533$).

Additional matrices using only the 6 and 9 most frequently occurring transition phrase types (with smaller degrees of freedom), were also analyzed and still showed significant sequential quasi-dependency ($P < 0.001$). Detailed calculations can be found in the Appendix A.

Table 3.4 and Figure 3.10 show the First-Order Markovian Dependency results in a matrix and transition diagram. The analyses of the 15 most frequently occurring transitions showed the percentage of occurrence out of *the total number of transitions* ($n = 416$). The transition diagram also demonstrates a prominent, cyclical sequential pattern. Separate transition diagrams made for each phrase type (starting ‘from’ phrase) is also provided to show the percentage of transitions from each *row total* of the matrix for comparison.

Table 3.4. *Organized Matrix of Observed count frequencies. The diagonal shows frequencies of zero as the matrix is asymmetrical and a phrase cannot follow itself. Table is read from the left Column to Row, e.g. transition from Phrase a to Phrase b occurred 44 times.*

		Next state														
		a	b	c	d	f	g	j	k	l	m	n	o	p	w	x
Start State	a	0	44	0	1	1	0	0	5	0	0	0	0	0	0	0
	b	0	0	0	76	3	0	0	2	0	0	0	0	0	0	23
	c	4	0	0	0	2	0	0	0	0	0	0	0	0	0	0
	d	0	0	0	0	0	0	42	0	0	0	0	0	0	0	18
	f	31	11	1	0	0	0	0	0	0	0	0	0	0	0	0
	g	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	j	0	0	0	0	0	1	0	0	44	0	0	0	0	0	0
	k	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0
	l	0	0	0	0	1	0	0	0	0	10	0	9	1	0	0
	m	0	0	0	0	1	0	0	0	0	0	1	6	0	0	0
	n	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
	o	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0
	p	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
	w	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
	x	0	0	0	0	0	0	44	0	0	0	0	0	0	0	0

The organized pattern of sequences was represented using a transition diagram showing their overall frequency of occurrence in percentages (Figure 3.11). Rare transitions with occurrences less than 1.0% were omitted. An overall cyclical relationship can be seen in Figure 3.11 where Phrase f is observed to transition back to Phrase a and continue onwards. Phrase k and Phrase x present an alternative ‘path’ transition, where they always occur between these particular phrases. In some instances, Phrase l directly transitioned to Phrase O, skipping the more usual occurrence of Phrase M.

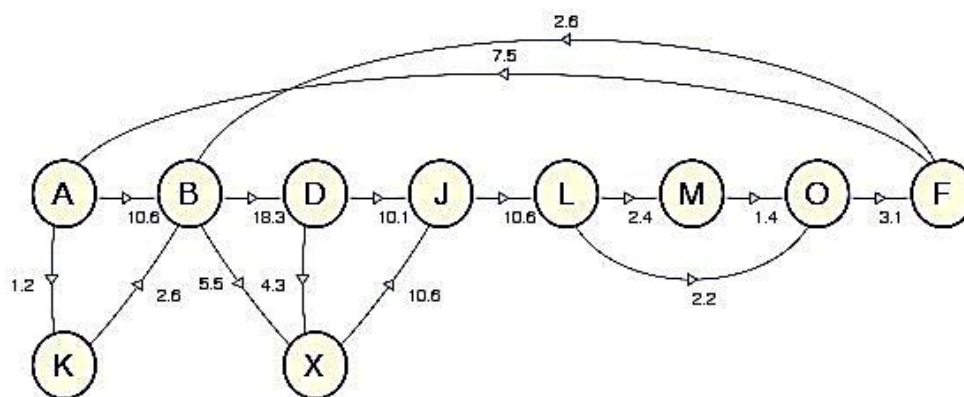
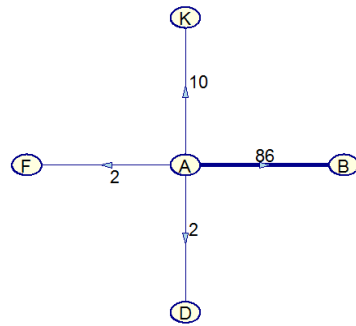


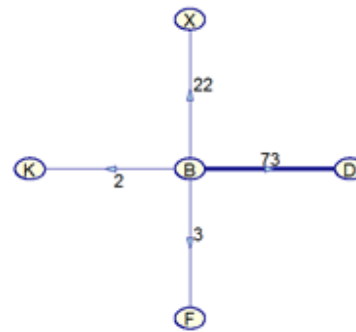
Figure 3.11. Transition diagram showing the most dominant phrase sequences and proportion (numbers are in %) of occurrence (out of the total 416 transitions). Circles with letters (phrase types are capitalized here) indicate Phrase type, starting from left to right, and arrows show the transition flow. Numbers shown in the diagram are in percentages. Rare transitions (<1.0%) were omitted. Note that the diagram reads left to right, however, it is important to understand that these phrase names are only for reference and that the pattern could actually start from any Phrase type name within this diagram.

Separate transition figures developed for each phrase type can be viewed in Figure 3.12. These show the proportion (in percentage %) of transitions per phrase type (*starting from phrase*) discerned by each row out of the row total from the matrix. It is important to notice that the diagrams are also indicative of which transitions are *absent* from each particular phrase type.

1) From A (n = 51)



2) From B (n = 104)



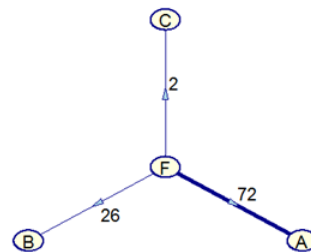
3) From C (n = 6)



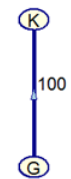
4) From D (n = 60)



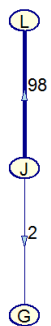
5) From F (n = 43)



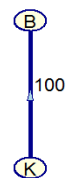
6) From G (n = 1)



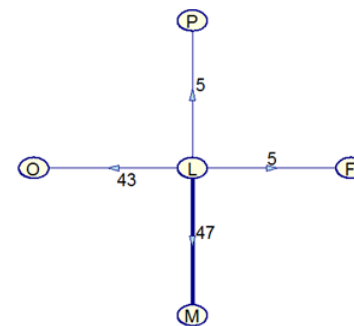
7) From J (n = 45)



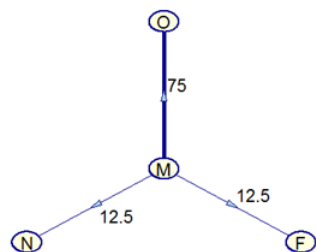
8) From K (n = 11)



9) From L (n = 21)



10) From m (n = 8)



11) From n (n = 2)

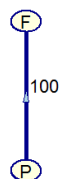


12) From o (n = 13)

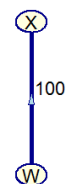


13)

From P (n = 4)



14) From W (n = 3)



15) From X (n = 44)



Figure 3.12. Transition diagrams (1-15) showing each phrase sequence and the proportions (numbers are in %) of occurrences (out of 'n'). Circles with letters (phrase types are capitalized here) indicate phrase type. Heavy set lines indicate the most prominent transition type. Arrows indicate the direction from a start Phrase. Numbers shown in the diagram are in percentages.

3.2.4 Phrase Analyses

A summary table with the nineteen phrase types and durations were shown in Section 3.2.2 Table 3.2. The table also provided the mean, maximum and minimum values per phrase type as well as the calculated standard deviations. The average coefficient of variances for all phrase types was approximately 24.6 %, ranging from a minimum variance of 12.47 % to 42.45 %. The phrase type with the longest measured (maximum) duration was Phrase b. The shortest phrase type recorded was Phrase f. The greatest standard deviation and coefficient of variance was found in Phrase a. Phrase I was recorded with the lowest standard deviation and coefficient of variance; however, there were only two occurrences measured for this phrase type. Phrase duration is also dependent on the number of unit repetitions found in each phrase. A boxplot is presented as a graphical method for displaying the medians and variation found in the phrase duration dataset (Figure 3.12).

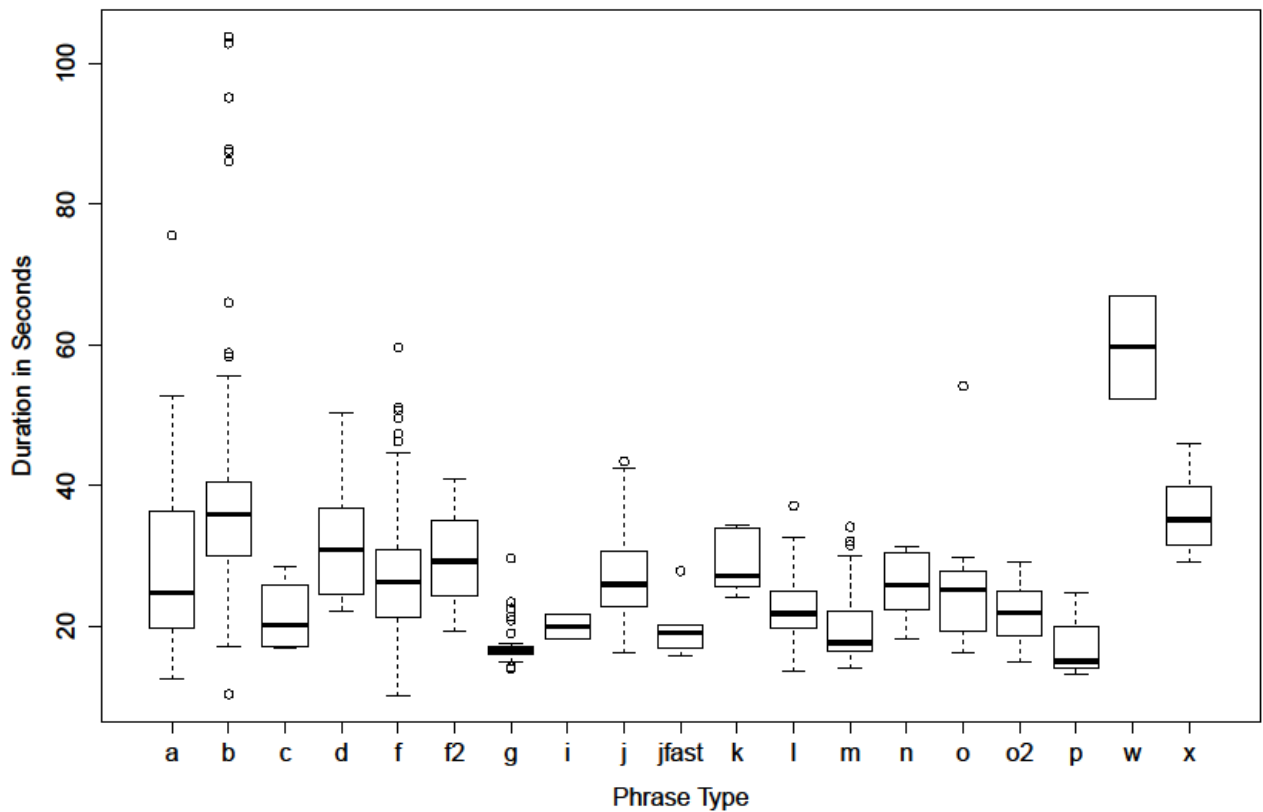


Figure 3.13. Box plot showing phrase duration distributions and variance for each phrase type ($n = 922$). Note that Phrase types (Phrase c, $n=4$; Phrase f2, $n=3$; Phrase i, $n=2$; Phrase p, $n=3$; and Phrase w, $n=2$) have low (< 5) sample sizes, though we show them here for consideration of their median values. The center line is the median value with the upper quartile displaying the values above which the upper 25% of the data are contained, and the lower quartile displaying the values below which the lower 25% of the data are contained.

Comparison of Durations between different Phrase Types

A non-parametric Kruskal-Wallis test was chosen because assumptions of normality and homogeneity were not met in all phrase types from the dataset. Results found that there was a significant difference between different phrase type durations (Kruskal-Wallis chi-squared = 385.2847, df = 18, P value < 0.001). Hence we reject the null hypothesis, and conclude that there are differences between the phrase type's durations.

A significant value from the Kruskal-Wallis test indicated that at least two groups differed from one another. Therefore a post hoc multiple comparisons test between treatments was applied to disclose which phrase types significantly differed from each other (P value = 0.05). Results indicated that 18% of the comparisons were found to be significantly different (31 out of 171 comparisons). Values can be seen in Table 3.5. Calculations from the Kruskal-Wallis and multiple comparisons test results can be found in the Appendix C.

Table 3.5. A multiple comparisons test after the Kruskal-Wallis test showed significant differences between these phrase types (P value ≤ 0.05). These phrase types (capitalized letters here) had higher calculated observed differences which exceeded their critical values. The top upper number in bold are the Observed Difference and the lower number represents the Critical Value.

Phrase	A	B	D	F	G	J	Jfast	L	M	O	O2	W	X
A	-	225.99 158.79	-	-	367.99 211.88	-	-	-	268.75 239.62	-	-	-	260.53 252.83
B	-	-	-	255.90 88.47	593.98 163.82	264.56 95.83	513.83 398.29	418.35 140.07	494.74 198.39	348.27 185.98	438.50 284.79	-	-
D	-	-	-	-	478.65 317.47	-	-	-	379.41 336.61	-	-	-	-
F	-	-	-	-	338.08 165.85	-	-	162.45 142.44	238.84 200.07	-	-	-	290.44 215.72
G	-	-	-	-	-	329.41 169.89	-	-	-	245.71 232.96	-	827.06 698.87	628.52 256.02
J	-	-	-	-	-	-	-	153.78 147.12	230.18 203.44	-	-	-	299.10 218.84
Jfast	-	-	-	-	-	-	-	-	-	-	-	-	548.37 444.23
L	-	-	-	-	-	-	-	-	-	-	-	-	452.89 241.51
M	-	-	-	-	-	-	-	-	-	-	-	727.83 707.77	529.28 279.41
O	-	-	-	-	-	-	-	-	-	-	-	-	382.80 270.74
O2	-	-	-	-	-	-	-	-	-	-	-	-	473.04 346.14

Comparison of Durations within the same Phrase Type

A non-parametric Kruskal-Wallis test was chosen and applied because assumptions of normality and homogeneity were not met for every phrase type; however some phrases did meet these assumptions. The Bonferroni correction was applied for comparisons to eliminate bias to obtain an adjusted P value ($P \leq 0.0055$). A Kruskal-Wallis test was applied for all phrase types. ANOVA tests were also completed as an additional measure to test for phrase types which did meet all assumptions (normal distribution and homogeneity of variances). Both tests were statistically sound and provided the same conclusions.

Three out of the nine phrase types were found to have significantly different durations within its phrase type ($P < 0.0055$). These were Phrase b (Kruskal-Wallis $\chi^2 = 28.0$, $df = 2$, $P \text{ value} = 8.225e-07$), Phrase f (Kruskal-Wallis $\chi^2 = 23.2$, $df = 2$, $P \text{ value} = 9.202e-06$) and Phrase l (Kruskal-Wallis $\chi^2 = 11.0$, $df = 2$, $P \text{ value} = 0.004016$). Hence we rejected the null hypothesis for these three phrase types, and conclude that there were significant differences within the Phrase type durations.

The six other phrase types, Phrase a (Kruskal-Wallis $\chi^2 = 2.2$, $df = 2$, $P \text{ value} = 0.3313$), Phrase g (Kruskal-Wallis $\chi^2 = 1.4$, $df = 2$, $P \text{ value} = 0.5073$), Phrase j (Kruskal-Wallis $\chi^2 = 3.4$, $df = 2$, $P \text{ value} = 0.1818$), Phrase m (Kruskal-Wallis $\chi^2 = 3.5$, $df = 2$, $P \text{ value} = 0.1731$), Phrase o (Kruskal-Wallis $\chi^2 = 1.2$, $df = 2$, $P \text{ value} = 0.5443$) and Phrase x (Kruskal-Wallis $\chi^2 = 1.4$, $df = 2$, $P \text{ value} = 0.506$) were not significantly different, showing $P > 0.0055$. Hence we accept the null hypothesis for these six phrase types, and conclude that there were no significant differences within the Phrase type durations.

Detailed calculations with both Kruskal-Wallis and ANOVA test results can be found in the Appendix D.

3.2.5 Themes

Themes were identified and analyzed when possible. Full songs encompassing all theme sequence starts and ends could not be always determined. However, 15 theme types could still be classified with a total of 316 defined themes, and 275 measured durations from start to end of a theme sequence (Table 3.6).

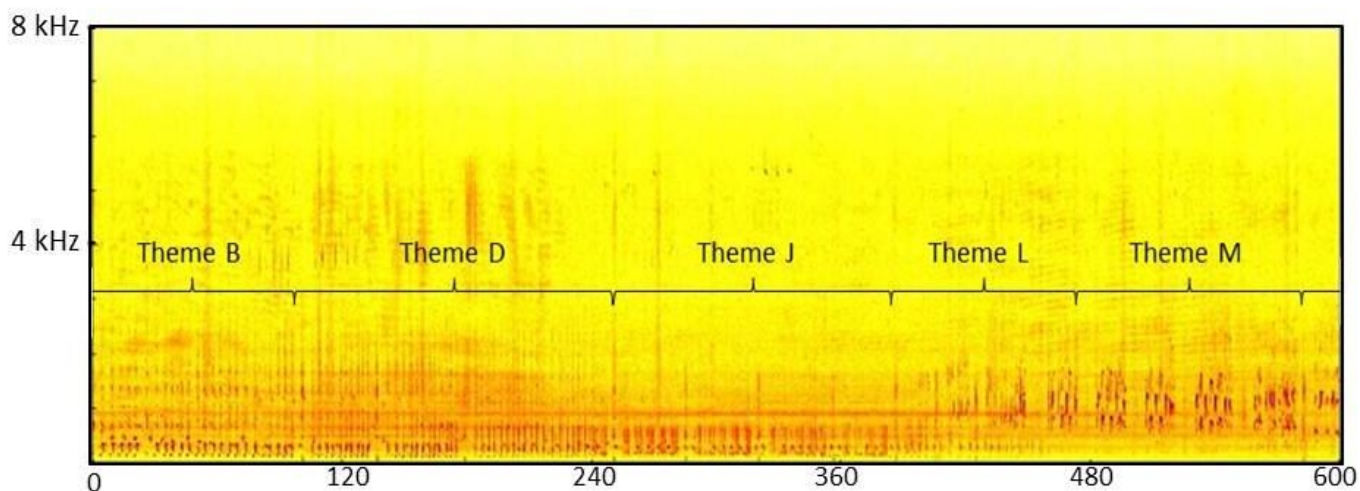
Figure 3.14 and Figure 3.15 demonstrate two high quality examples of consecutive spectrograms with reoccurring, sequential theme patterns. Although there is a 5 minute break interval, the 30 minutes of visually presented recordings strongly represent a definite cyclic pattern of themes being sung in sequence. As there are two, 5 minute break intervals in between the three consecutive spectrograms, these figures could present songs or a song session with a length of approximately 40 minutes in total duration. A conservative minimum of the spectrograms show that there are at least three songs, with a minimum duration of 10 minutes.

Table 3.6. Summary table showing calculations of identified themes with and without durations. The counts, percentage, measured averages, maximum and minimum values, standard deviations and coefficient of variances are also provided below.

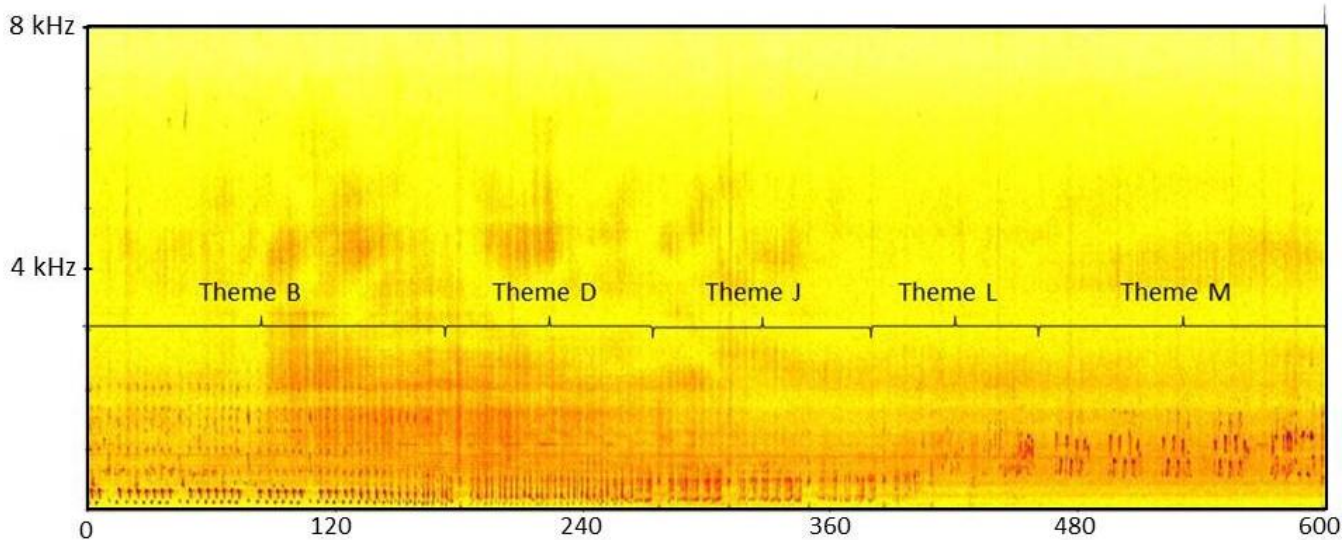
<i>Theme Type</i>	<i>Total Count (n)</i>	<i>Percent</i>	<i>Count with Durations</i>	<i>Average Duration (sec)</i>	<i>Max</i>	<i>Min</i>	<i>Standard Deviation (SD)</i>	<i>Coefficient of Variance</i>
Theme A	16	5.1	16	115.1	208.9	64.2	46.4	40.3
Theme B	84	26.6	76	175.8	552.4	62.7	107.4	61.1
Theme C	1	0.3	1	84.9	NA	NA	NA	NA
Theme D	6	1.9	6	89.3	148.8	67.8	32.6	36.5
Theme F	57	18.0	46	145.6	329.3	42.6	86.1	59.1
Theme G	12	3.8	10	70.2	184.5	33.8	49.8	70.9
Theme J	65	20.6	56	94.4	367.6	40.4	61.1	64.7
Theme K	4	1.3	4	63.3	75.9	54.9	10.0	15.8
Theme L	26	8.2	19	70.3	199.1	34.9	47.1	67.0
Theme M	11	3.5	10	76.2	125.0	38.8	34.5	45.2
Theme N	1	0.3	1	138.4	NA	NA	NA	NA
Theme O	16	5.1	14	66.8	119.2	38.1	31.9	47.8
Theme P	2	0.6	2	60.3	61.4	59.2	1.6	2.6
Theme W	2	0.6	2	118.8	162.2	75.4	61.4	51.7
Theme X	13	4.1	11	90.8	129.7	66.3	41.9	46.2
Total	316	-	275	-	-	-	-	-

Themes are composed of repeated, similar phrases, thus by definition, a new phrase type (or transition phrase) within the sequence would initiate a new theme. A ‘dominant’ starting theme would be categorized as the Theme type denoted here. This was due to the nature of themes usually including a transition phrase before changing to a new theme type. All themes and the transition types can be found in the Appendix F.

I) 13 February, 2011 at 17:30



II) 13 February, 2011 at 17:45



III) 13 February, 2011 at 18:00

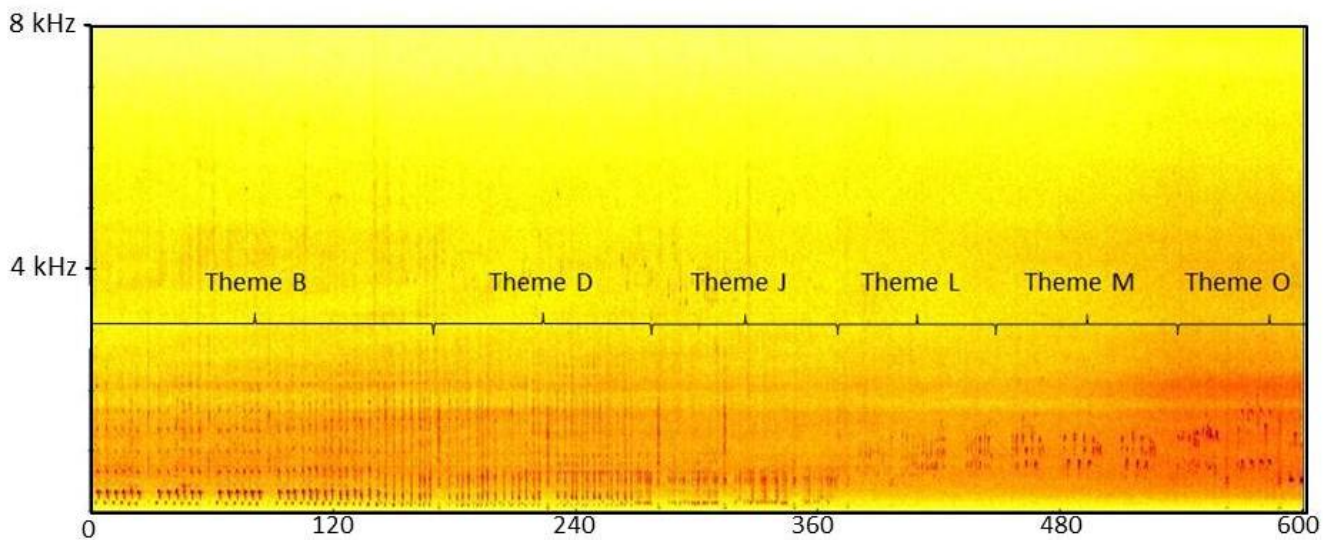
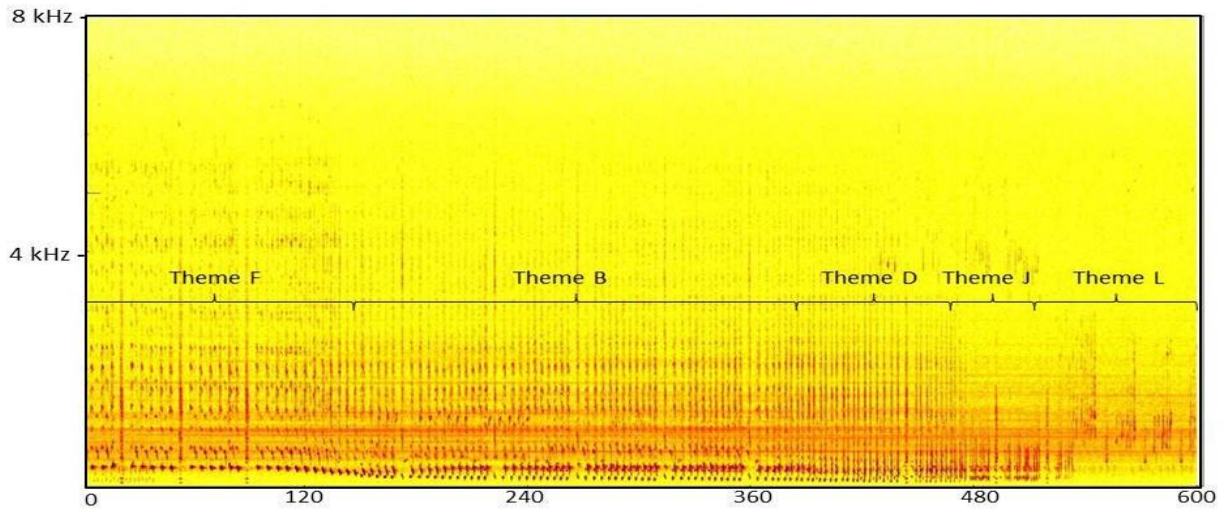
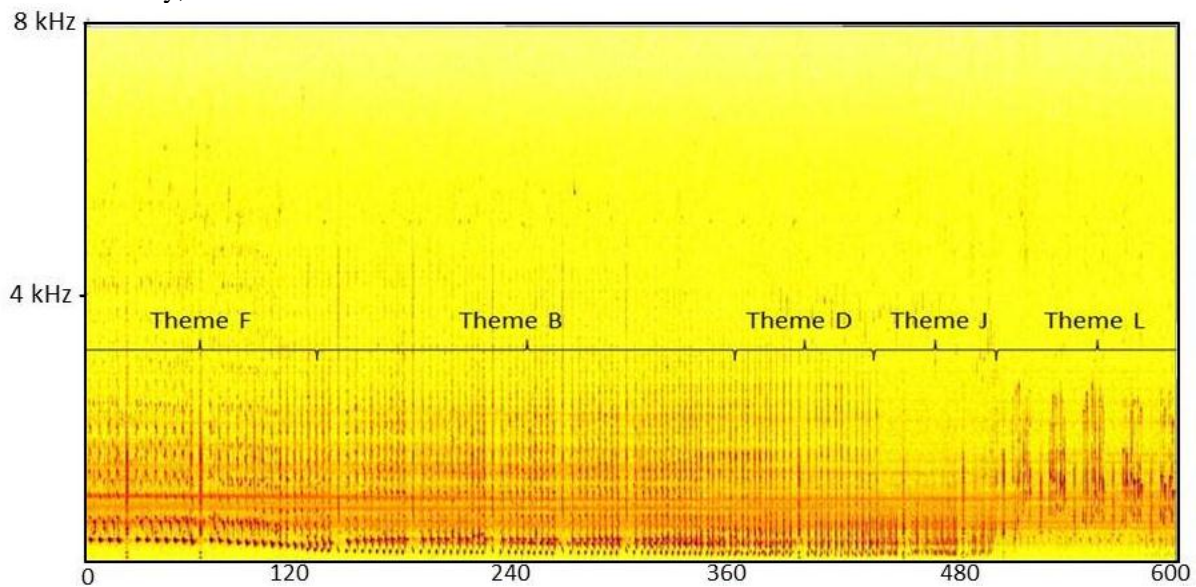


Figure 3.14. Figures of three consecutive wav files (30 minutes) with reoccurring themes. Distinct cyclical song patterns are shown. Spectrograms reach a maximum of 8 kHz. FFT size: 1024, Hanning window, 85% overlap.

I) 19 February, 2011 at 18:30



II) 19 February, 2011 at 18:45



III) 19 February, 2011 at 19:00

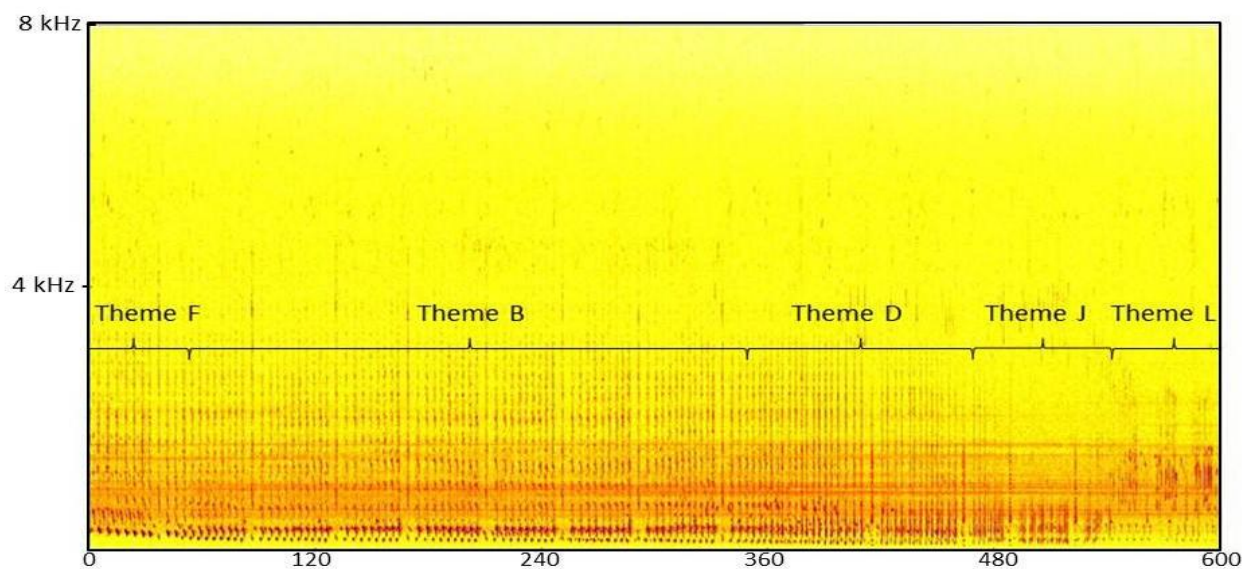


Figure 3.15. Figures of three consecutive wav files (30 minutes) with reoccurring theme patterns. Distinct cyclical song patterns are shown. Spectrograms reach a maximum of 8 kHz. FFT size: 1024, Hanning window, 85% overlap.

Comparison of Durations between different Theme Types

The durations of themes were compared between 13 of the theme types to find if there were any differences between them. Only themes with frequencies >1 were analyzed, thus Theme C and N were omitted from the calculations. Figure 3.16 shows a box plot figure of the theme duration distributions.

Results from a non-parametric Kruskal-Wallis test found that there was a significant difference between different phrase type durations (Kruskal-Wallis chi-squared = 102.126, $df = 12$, P value < 0.001). Hence we reject the null hypothesis, and conclude that there are significant differences between the different Theme type's durations. A significant value from the Kruskal-Wallis test indicated that at least two groups differed from one another. Therefore a post hoc multiple comparisons test between treatments was applied to find which theme types significantly differed (P value ≤ 0.05).

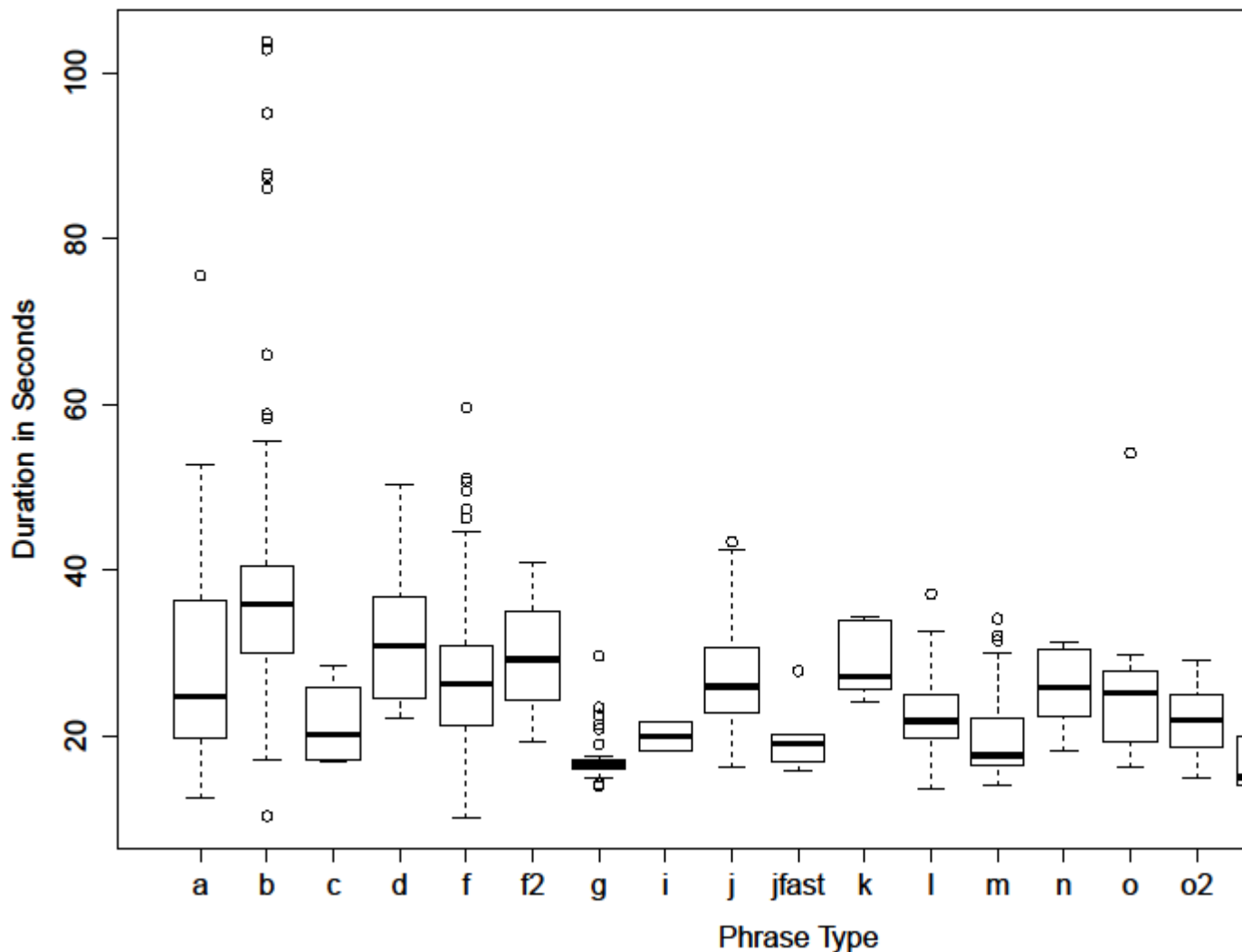


Figure 3.16. Box plot showing theme duration distributions and variance for each theme type. Note that Theme C and N were omitted.

for consideration of their median values.

Results showed that 10.25% of the comparisons were found to be significantly different (8 out of 78 comparisons) (Table 3.7). Detailed calculations from the Kruskal-Wallis and multiple comparisons test results can be found in the Appendix G.

Table 3.7. Multiple comparisons test after Kruskal-Wallis showed significant differences between these theme types (P value ≤ 0.05). The calculated observed difference must exceed the critical values in the right column to be significant. The top upper number in bold are the Observed Difference and the lower number represents the Critical Value.

Theme	B	F	G	J	L	M	O
B	-	-	-	84.53	125.93	105.01	124.76
				47.29	68.88	90.33	78.10
F	-	-	109.35	67.62	109.02	-	107.85
			93.69	53.43	73.23		81.96

4 Discussion

The results confirm that humpback whales commonly sing in a subarctic feeding ground of Iceland during the winter breeding season months, January to March. The findings markedly expand and support the 2008 and 2009 investigation of song units by Magnúsdóttir *et al.* (2014). Recordings from the previous study did not include mid-February to March and complete song structures could not be previously represented. The previous findings from 2008-2009 showed that song signals peaked in winter months, especially before the end of the recording period in early February. Thus, the timing of detections from this thesis study complemented accordingly with those in 2008-2009. The results also demonstrated extensive song occurrence in months that had not been previously recorded. Using longer recording methods focused in winter months, this study described and characterized song pattern and organization discovered in Iceland's high latitude feeding ground.

The precise use of this high latitude feeding ground in Iceland is still not yet fully understood. There are often logistical difficulties for studying cetaceans in high latitude areas during winter time. Research is considered impractical due to limited light conditions and adverse sea and weather conditions. Therefore, passive acoustic monitoring is especially valuable during winter time in such a high latitude area. Using EARs for data collection, the findings here have helped provide a greater insight into the winter time humpback whale behaviour for this high latitude area. It is important to note that although there may not be acoustic detections of vocal activity, it does not necessarily mean that no humpback whales were present, as they might not have been vocalizing at the time or moved periodically out of the area.

Humpback whale song vocalizations were detected on each and every day, from 25 January to 12 March, 2011. The numbers of detections found per day peaked on 16 February, 2011. The numbers of detections found in each wav file were also highly indicative of whether there would be more than one individual singing in the same spectrogram file. In general, greater than 150 detections in one file showed more than one humpback whale chorusing in partial intervals of the spectrogram. Files with greater than 300 detections showed multiple singers chorusing in the entire extent of the file (multiple singers were associated with visual and aural overlapping of units and phrases found in the spectrograms). The results showed that a quarter of the recordings detected more than one individual humpback whale chorusing together with other conspecifics. These overlapping units and phrases showed that many singers were present and associating with each other. However, the overlaps were not visually counted to determine the actual number of singers. Overlapping phrases and units indicated that at least two whales (or more) were singing at the same time.

Though the majority of song occurrences are still mainly attributed to established mating and breeding grounds of tropical low latitude aggregation areas, more and more findings

certainly show that singing is no longer an explicit behaviour confined to these tropical areas. Songs have been recorded in numerous mid-to-high latitude feeding grounds, including feeding grounds located in the North Atlantic and North Pacific (Baker *et al.* 1985, Mattila *et al.* 1987, McSweeney *et al.* 1989, Clark and Clapham 2004, and Vu *et al.* 2012). Frequent reports of singing during migration have already shown the plasticity of singing behaviour outside of regular breeding grounds (Clapham and Mattila 1990, Norris *et al.* 1999, Charif *et al.* 2001). Many of the earlier studies, prior to Clark and Clapham's study from 2000, were short-term, opportunistic findings. Intermittent recordings of song in the North Atlantic were discovered by Mattila *et al.* (1987) from March through November, in the Stellwagen Bank National Marine Sanctuary (mid-latitude feeding ground). One full song was recorded in south-eastern Alaska by McSweeney *et al.* (1989) on one day in August 1979 and in one day of September 1981. Findings from both studies indicated that singing usually occurred during late autumn months on feeding grounds right before migration was expected to begin. Clark and Clapham (2004) employed the first long-term continuous acoustic monitoring program for humpback whales feeding in the Stellwagen Bank National Marine Sanctuary. Clark and Clapham (2004) found a daily occurrence of song during the spring months, May to June, in 2000. One of the most recent acoustic studies, from the North Atlantic, was reported by Vu *et al.* (2012) who described continuous year-long singing from a mid-latitude feeding ground. Vu *et al.* (2012) found songs in almost every month of the year, with increased singing detected during shoulder seasons of spring, from April to May and late fall from October to December (2006 to 2008). However, in contrast to the studies in Iceland, Vu *et al.* (2012) found that almost no song occurrence was detected in the winter months of January to March. Another interesting report by Stimpert *et al.* (2012) discovered underwater dive and foraging behaviour of humpback whales during song production at a high latitude Antarctic feeding ground in the Southern Hemisphere. In Stimpert *et al.*'s (2012) study, suction-cup tags were deployed on humpback whales and recorded singing into late austral fall, between May and June of 2010. Once again, the results from that publication supported studies of shoulder season singing; in the beginning and end of mating season (ie. fall or spring).

The prominent level of hierarchical structure associated with the wintering songs in this Icelandic feeding ground was unexpected, given that this behaviour is associated with mating and breeding behaviour at lower latitudes. The clear patterns of organization and sequence structure in the songs were characteristic of mating ground song vocalizations described by Payne and McVay (1971). The results were also comparable to song phrases identified from high latitude feeding grounds (Clark and Clapham 2004, Vu *et al.* 2012) and from mating grounds in the West Indies and Cape Verde islands (Winn and Winn 1978, Winn *et al.* 1981, Mattila *et al.* 1987, Guinee and Payne 1988).

A growing body of literature indicates that song detection outside of the breeding ground is not as unusual or as static as previously assumed. However, unlike most studies from high latitude feeding grounds, peak song occurrence here was also associated with the peak mating season. The results from this thesis study showed that singing occurred nearly every day with recordings of multiple humpback whale singers. The importance of these findings also demonstrated that singing was continual and not an irregular event.

4.1 'Icelandic' song characteristics

Phrases

Phrases are the fundamental pattern of repetition, containing from 2 to over 20 units, and ranging from under 10 seconds to over 30 seconds in duration (Payne and McVay 1971, Cerchio *et al.* 2001). The complexity and variation depends both on the number of unit repetition as well the composition of unit types and subphrases (Cerchio *et al.* 2001).

There were 19 phrase types characterized in total. The five dominant phrases (observed > 15% of the time) included Phrase a (29.6%), Phrase b (28.2%), Phrase f (23.8%), Phrase j (18%) and Phrase l (6.3%). Phrase b was the most dominant phrase type from this recording period. Variations of a phrase type were more likely to be separated into their own category or subcategory because phrase types could be grouped more easily later. Therefore, it is possible that a higher number of phrase types may have been characterized, due to the positive bias towards classification and separation into groups. The five most prevalent phrases (Phrase a, b, f, j and l; observed > 5% of the time) and frequently observed transition phrases (Transitions a-b, b-d, d-j, j-l, x-j; observed > 10 %) likely reflect and characterize the most prevalent songs from this area.

Phrase durations are described as a stable feature of humpback whale song since minimal variation is found between individuals of a given population (Payne *et al.* 1983, Cerchio *et al.* 2001). To address if there were any significant discrepancies within a measured phrase type, durations from the same phrases were compared within the same phrase types in addition to calculating their coefficient of variance. The majority of frequently observed phrases did not show any significant difference within the phrase type. However, three of the nine analyzed phrases (33.3%) had significantly different durations. These included Phrase b, Phrase f and Phrase l. This durational difference was also reflected in the large ranges found between the measured minimum and maximum values. However, although Phrase a had the largest calculated coefficient of variance, it did show as being significantly different in the results. The significant differences found in the three phrases could be the consequence of making group divisions affected by temporal differences. The three groups were divided evenly to have similar sample comparison sizes (explained in the Methods Section). These groups of numbers may have been temporally dependent, thus the first group division would be samples taken from an earlier period in time, and the third group was analyzed from the latter period. The time period of recordings were not compared for this section mainly due to inconsistent differences in sample sizes. The numbers per grouping would also depend on how many counts were observed in total throughout the data analyses. Only phrase types with high frequencies were analyzed since the statistical analysis and power was dependent on sample size. As songs are known to evolve constantly and dynamically over time, significant differences may have been attributed to the changing variation in the phrases. A significant difference was found in one of the most prevalent phrase types of this recording period and may reflect durational change and variation in the Phrase b (Payne *et al.* 1983, Payne and Payne 1985, Cerchio *et al.* 2001).

Song lengthening has been observed in other studies where humpback whales sang old themes more slowly than their newly learned ones during breeding season (Payne *et al.* 1983, Payne and Payne 1985). Perhaps this variation found in phrase duration was indicative of arising song change taking place over the 2011 winter season of recordings. Duration changes may also be attributed to change in each unit length or increased break intervals between every unit repetition (Eriksen 2003). Another consideration is that the phrase type categorizations did not differentiate between phrases with or without primary subphrases. Both types (phrases with primary subphrase types and those without) were categorized together and may have differed durations. Thus, this non-discriminatory categorization could explain the observed durational differences found in the results. Guinee and Payne (1988) determined that most of the changes in songs operated at the phrase level, though more long-term significant changes in themes occurred over multiple years. A more detailed analyses focusing on unit types would be useful to further understand the durational variation found in this study.

A comparison of phrase durations between differing phrase types revealed significant differences between them. Therefore, song duration would not only depend on how many repetitions of phrases occur, but also on the types of phrases sung. The most dominant phrase type, Phrase b, had the longest maximum phrase duration and a very long average duration. Phrase w, which was composed of both Unit b and Unit j, is an example of how measured duration was affected by phrase type composition. Therefore, differing phrase types likely affect the overall measured durational changes in themes as well as songs since these are composed of repeating phrases.

Phrase durations from this study had an approximate average of 27.3 seconds ranging from the shortest phrase, measured at 10.1 seconds (Phrase f), to an exceptionally long phrase measured at 103.8 seconds (Phrase b). The average phrase durations found in this study area, appeared to be relatively longer in duration (all phrase type averages were > 15 seconds) than those observed from other given phrase measurements in Cerchio *et al.* (2001) and Eriksen *et al.* (2003). Cerchio *et al.* (2001) described typical phrase durations from the Hawaiian Islands and Isla Socorro off the coast of Mexico, and provided average phrase durations ranging at approximately 10 seconds. Eriksen's (2003) study of songs from Tonga showed a maximum phrase duration recorded at 78.51 seconds. However, phrase averages from there were approximately 11 seconds, with the shortest phrase measured at only 0.4 seconds. It was noted that the longest phrase duration found in the Eriksen (2003) study was attributed to the multiple subphrases found in 1991, which was not identified between 1993 and 1998. In the current thesis study for northeast Iceland, subphrases (z1 and z2) were almost always associated with all the defined phrase types and commonly observed in every spectrogram. Example spectrograms published by Vu *et al.* (2012) also showed a similar pattern of multi-subphrases, with a primary subphrase composed of one unit. Visual comparison of Vu *et al.*'s (2012) example spectrograms also showed a downswept harmonic unit which resembled the primary Subunit z1 from this current thesis study. A few exceptions from this study, noted that a few phrases were not always in sequence with a primary subphrase (z1 and z2). These were Phrase l, Phrase m and Phrase n. The frequent association of subphrases commonly found in the winter recording period for this thesis study may be a unique attribute linked to the population in Iceland, where longer phrase types are reflective of the frequent use of multiple subphrases throughout the song.

Themes

The themes from this current thesis study demonstrated consistent patterns of song organization and hierarchical structure similar to other studies with spectrogram song examples from mating grounds (Payne and McVay 1971, Winn *et al.* 1981, Mercado *et al.* 2003, Murray *et al.* 2012, Cholewiak *et al.* 2013). The identified themes were a direct expression of the analyzed phrases. Consequently, the hierarchical composition of different types of phrases and the number of phrase repetitions affected the overall duration of the theme. A total of 15 theme types were categorized and analyzed. The most prevalent themes were identified as Theme B (26.6%), Theme J (20.6%) and Theme F (18%). These themes occurred > 10 % of the time and clearly represented the most commonly characterized phrases. The dominant theme type from this recording period was Theme B. As other song studies demonstrated, particular song patterns (ie. themes) could be observed in more than 50% of the recording periods (Gill *et al.* 1995, Mercado *et al.* 2003). The dominant characteristics provided a unique identity and representation of the humpback whale population. Theme B was the most common song pattern identified more than 25% of the time from this thesis study's high latitude feeding ground. As expected, and consistent with Cholewiak *et al.* (2013), the durations from the measured theme types expressed a greater variability and had higher coefficient of variance values than the phrase durations. Since humpback whales change their singing over time and previous themes are sung more slowly than new themes, this attribute may explain the greater durational variability found in the results.

Themes have been categorized into different types by Payne and McVay (1985) as 'static', 'shifting' and 'unpatterned' themes. Static themes are described as nearly identical phrases, shifting themes have successive phrases evolving progressively with unit transformations varying in frequency, form, duration, and/or counts and unpatterned themes show no clear structure or organization. The themes from the current thesis study results were mainly static, though shifting themes were sometimes observed and could be delineated by their secondary, variant phrase types (ie. Phrase F2, O2 or Phrase Jfast). For the purpose of the study, shifting themes and phrases were not analyzed in detail. However, Murray *et al.* (2012) showed in a study from the Indian Ocean, that the analyses of phrase structures and unit transformations within a theme can be useful for population comparisons. It is important to recognize the many varying degrees of theme types which can be a precarious element of song to characterise. Cholewiak *et al.* (2013) suggested that definition of themes needed to be clarified to minimize author bias. It was emphasized to characterize phrase structures to maintain a more consistent method of song evaluation. Cholewiak *et al.* (2013) aimed at minimizing and standardizing the comparison of songs between different regions and different time periods. That approach was applied in this thesis study to minimize bias and maintain consistency for any further research of this 2011 dataset.

Predictable pattern and sequences

Transition phrases directly indicate the change and patterns of organization taking place within a song. These transitions revealed significant associations present in the 2011 winter recordings. Since a sequence of similar phrase types defined a theme, transition phrases also indicated the initiation of a new phrase type and the start of a new theme type.

A definite pattern of predictable phrase association was found from the transition phrase analyses in this study. Sequential order and patterns were investigated using first-order Markovian sequencing. This is a common method used to interpret bird song organization and predict dependent behavioural states (Lemon and Chatfield 1971, 1973, Dobson and Lemon 1979, Katahira *et al.* 2011). The consistent transition order showed that the sequences were highly invariant and phrase transition reversals did not occur throughout the entire recording period. However, there were some less frequent phrase transitions observed between particular phrase types. In these instances, a modified transition order would take place instead of the more common association. For example in (Figure 3.11), the use of Phrase k sometimes occurred in between Phrase a to Phrase b. Phrase b or Phrase d would also transition to Phrase x in some instances before Phrase j. It was also found that in a few transitions, a phrase was ‘skipped’, as seen from Phrase l to Phrase o, where Phrase m was absent. These alternate paths were, however, still predictable and always occurred in these ordered instances; albeit less frequent in comparison to its counterparts.

The reoccurring phrase type associations were undeniably dependent on prior states, revealing a visually evident cyclical pattern. When there are frequent variations from normal song cycles, these songs are classically referred to as “aberrant song sessions” (Frumhoff 1983). ‘Aberrant’ songs are regarded as song cycles that vary from the norm and have high degrees of theme reversals. This song type is generally regarded as uncommon for mating ground humpback whale songs (Frumhoff 1983, Cholewiak *et al.* 2013). However, Cholewiak *et al.* (2013) describes that higher degrees of variation in theme order is more usual than traditionally defined. Songs from multiple breeding ground areas display ‘aberrant’ and ‘variable’ characteristics, but are still regarded as mating ground song (Cholewiak *et al.* 2013). The humpback whale songs described from this current thesis study did not show substantial aberrant song characteristics. No transition reversals were found and a clear cyclical pattern was visibly evident. However, occasional variation did occur in individual phrase transitions seen in Figures 3.12. The variation and transition diversity found in some phrase types suggested that the songs may be undergoing continual change. For example, in Phrase b transitions (Figure 3.12-2), the predominant transition is from b to d (73 %). However, transition b to x also occurs at 22 %, which may indicate that a developing change is occurring at the transition level. As time progresses, transition b to x may either be phased out completely, or become the most dominate transition type. The most infrequent or rare transitions found in the results could also indicate that these transitions may eventually be phased out after a period of time. Song evolution and changes commonly occur during one breeding season; however, high degrees of variation takes time and is observed over multiple successional years (Payne and McVay 1971, Winn and Winn 1978, Payne and Payne 1985, Eriksen *et al.* 2005). Therefore, higher diversity for each phrase type observed here may reflect a part of a larger, long term change or evolution for each particular sequence (Cholewiak *et al.* 2013).

The most common phrase types identified for this winter period appeared to have some analogous patterns to the most common unit detections described in 2008 and 2009. ‘Unit A’ and ‘Unit E’ from the previous study of Magnúsdóttir *et al.*’s (2014) are very similar to 2011’s Phrase a and Phrase m types. Units that had been present for 2008 and 2009, were also absent from this 2011 winter season (ie. ‘Unit I’ is not found here in 2011). The majority of 2011 units described in this thesis study were not previously detected in 2008 and 2009. This change is indicative of progressive song modification over the 2008 to 2011

recording period. With only one season of song analyses, it is not possible to discern exactly how the songs are evolving and changing across multiple years; however, it still reveals that song modification is taking place in this subarctic feeding ground.

The process of change in songs is considered to occur through cultural transmission and vocal learning between individuals (Payne and Guinee 1983). Direct transmission and sharing can take place through mixing and communication between individuals on feeding grounds or during migration (Payne and Payne 1985). Studies indicate that the majority of song changes take place throughout the winter season, when singing is at its highest, thus less change is observed in the summer months. Analyses of humpback whale songs from the West Indies and Cape Verde islands also find song similarities between them showing that exchanges do occur amid the two breeding grounds (Winn and Winn 1978, Payne *et al.* 1983, Smith *et al.* 1999, Cerchio *et al.* 2001). Perhaps the social interaction and song exchange from the two separate breeding ground areas of Cape Verde and West Indies is occurring in this shared Icelandic feeding ground. This potential interaction and exchange on a high latitude feeding ground could be the driving force behind continued cultural transmission and song exchange observed for these populations.

Duration comparison

In McSweeney *et al.* (1989), comparison of songs showed that Southeast Alaskan feeding ground songs were significantly shorter than those in Hawaiian breeding grounds. The full songs recorded from Alaska, lasted only 124 seconds, whereas the songs, found during winter time in Hawaii, averaged 643 seconds (McSweeney *et al.* 1989). Full song durations generally range from 7 to 30 minutes, like those in the Hawaii observations. Furthermore, songs within this range correspond to the typical description of breeding ground songs (Payne and McVay 1971). In the current thesis study from northeast Iceland, single themes range from 60 to 176 seconds. In contrast to the songs found in McSweeney *et al.* (1989), the songs here in Iceland demonstrate a greater durational similarity to songs observed from tropical breeding and mating grounds since themes were already measured to be longer than complete songs from Southeast Alaska. In Figure 3.14 and 3.15, three high quality, 10 minute spectrogram examples recorded in temporal succession from February 13 and February 19, showed 30 minutes of themes sung in succession, indicating at least 40 minutes of song session when including the 5 minute interval breaks not observed in between the spectrograms. Although the 5 minute intervals are not displayed, it is very unlikely that these 5 minutes would be significantly different from the analyzed 10 minute successive song patterns, since a repeating theme structure was already observed. Thus, it is reasonable to assume that the themes are part of the same song. At minimum, a conservative estimate would find that these individual spectrograms indicate multiple song recordings of at least 10 minutes in duration per song. The consecutive spectrograms indicate singing by one individual. As described by Frumhoff (1983), a complete song is composed of ‘at least three themes which are repeated in the same order, two or more times during a recorded song session’. This description was observed and delineated in multiple spectrograms from this research thesis. As discussed in Cholewiak *et al.* (2013), song duration measurements are highly dependent on the interpretation of themes occurring in each cycle of a song. Therefore, theme orders in longer songs need to be distinguished as variant or invariant. The findings of variance or invariance would consequently influence

the measurement of song durations, since less stable theme orders are more difficult to define and measure.

4.2 Overwintering and Tradeoff Strategy

Clark and Clapham (2004) suggest that the energetic costs of remaining in cold waters at higher latitudes could also be more than compensated for by feeding and utilizing an abundance of prey during the winter time. Singing humpback whales have recently been tagged and observed during periods of active foraging behaviour in the high latitude feeding grounds of the Antarctic during austral spring and fall (Stimpert *et al.* 2012, Garland *et al.* 2013b). Unexpected findings by Stimpert *et al.* (2012) demonstrated song production in close overlaps between singing and feeding behaviour during periods of active dives at depths greater than 100 m. Their studies indicate that a tradeoff strategy between foraging and mating behaviour is highly applicable to the humpback whale species on winter feeding grounds, where spatial and temporal limitations are not as restrictive as previously assumed. Since Skjálfandi Bay is known to be nutrient rich and high in prey abundance, it has been proposed that individuals delay their migration or overwinter altogether in this subarctic feeding ground (Magnúsdóttir *et al.* 2014).

A humpback whale photo identification catalogue was developed since 2001 by the Húsavík Whale Museum and since 2007 by the University of Iceland's research center in Húsavík. It shows the continual return and reoccurrence of multiple humpback whale individuals in Skjálfandi bay (Dr. Marianne Rasmussen, Húsavík Research Center pers comm.). A preliminary study comparing the individual humpback whale photo identifications in Skjálfandi Bay as well as the neighboring bay Eyjafjörður, to the west of Skjálfandi, and in southwest Faxaflói Bay, has already identified individuals occurring both in the late autumn and winter months. Individuals have also been identified during the summer months in the same year, suggesting that overwintering humpback whales are staying year-round in this subarctic feeding ground (Loes de Heus, *pers. comm. current Master's research thesis*). Humpback whales are also being identified from multiple neighboring bays, demonstrating traveling and interchangeable use between Iceland's coastal waters. These findings verify that the same population is overwintering around the coast of Iceland, most likely in pursuit of prey. Loes de Heus's research provides important evidence that individuals are staying in their feeding grounds in Icelandic coastal waters during winter and summer months. This evidence also supports the likelihood that at least part of the population does not migrate but instead, overwinters in Icelandic waters.

Overwintering of humpback whales is not a new behavioural anomaly for feeding grounds. Studies have already found humpback whales and fin whales overwintering in high latitude feeding grounds of the Arctic as well as in the Antarctic (Simon *et al.* 2010, Opzeeland *et al.* 2013). From the Southern Hemisphere, Ozeeland *et al.* (2013) found acoustic presence of humpback whales throughout austral winter and summer indicating that they are overwintering in an area with accumulating sea ice presence. Recent satellite taggings indicate that humpback whales left their breeding grounds by mid-April, traveling northwards towards Iceland and/or the Barents Sea of Norway (Kennedy *et al.* 2014). This variability in humpback whale wintering and migration behaviour clearly reinforces the

complex considerations needed for this species. The choice to migrate appears to vary by individual and is evidently affected by multiple ecological factors. Furthermore, the choice is possibly related to gender, prey availability and timing in relation to sexual maturity and reproductive periods. Since humpback whales are recorded singing, this indicates that males are overwintering. It is also likely that female humpback whales are doing the same to avoid the energetically costly migrations (Brown *et al.* 1995, Craig and Herman 1997, Smith *et al.* 1999).

It is possible that over that last few decades of trying to gain a better understanding of this fascinating baleen species, researchers were missing important geographical locations in higher latitudes outside of the more obvious warm water mating grounds. Perhaps humpback whales have always overwintered and partaken in late migrations from many or most mid to high latitude feeding grounds. Previous equipment capabilities could have also limited the ability to detect songs at high latitude feeding grounds (Clark and Clapham 2004). It is interesting to consider two hypotheses that could explain the behaviour of humpback whales in Skjálfandi Bay: 1) humpback whales have always behaved this way, or the behaviour was more recently developed as more individuals overwintered and participated in later migrations to maximize prey abundance; 2) the later migrations and overwintering may have developed more recently in this area because humpback whales are capable of doing so, or are required to do so in order to adapt and adjust to their changing environments.

Song vocalizations likely serve several functions for humpback whales. The general consensus is that songs are a form of vocal communication used by males for intersexual display for attracting female mates and competitive intrasexual display with other male conspecifics (Tyack 1981, Clark and Clapham 2004, Smith *et al.* 2008). Singing is primarily associated with sexually active males, suggesting that singing behaviour plays an important role in mating function and maximizing reproductive opportunities for increased contact and mating (Herman *et al.* 2013). According to Winn and Winn (1978), humpback whales may apply ‘communication theory’ to the use of song signals. According to this theory, redundancy of signals within a song would increase the likelihood of sending a correct message to the receiver and differentiate the message from ambient noises. The detectable repetition and stereotypy patterns indicate that the success and efficacy in conveying and accentuating a message and vocal learning, is also associated with the complexity, duration, and overall novelty of the songs (Smith *et al.* 2008, Green *et al.* 2011). Thus, sexual selection would further favour dynamic song patterns attributed to humpback whale songs and result in increased female (signal receiver) preference of these conspicuous song features. The intersexual display of songs outside of the usual warm water breeding grounds could represent a low-cost opportunistic mating behaviour. Thus, an increase in reproductive success would still be possible while exploiting high prey availability (Clark and Clapham 2004). Because song is presumed to play an important function in the humpback whale’s reproductive success, then the singers recorded in this subarctic feeding ground are displaying an important behaviour related to mating (Tyack 1981, Darling and Berube 2001, Smith *et al.* 2008, Herman *et al.* 2013). Not only does the seasonal period of this heightened reproductive potential coincide with the peak times in singing, the song characteristics are also analogous to the hierarchically structured songs from mating grounds.

Singing behaviour has been linked to elevated hormonal levels observed in sexually mature males along with heightened testosterone levels and increased testes weight found during the reproductive winter season (Nishiwake 1959, 1960, 1962, Clark and Clapham 2004). This relationship is further supported with marked declines of song detection during summer months from North Atlantic feeding ground studies (Clark and Clapham 2004, Vu *et al.* 2012, Magnúsdóttir *et al.* 2014). Furthermore, the timing of winter conception coincides accordingly with the main calving period. Gestation takes approximately 11 to 12 months; hence the calving period also occurs during the winter between December to April, peaking in February (Chittleborough 1958).

The extensive singing behaviour found in the results of this research thesis and in 2008-2009 of Magnúsdóttir *et al.*'s (2014) study, is likely stimulated by higher testosterone levels that coincide with the same timing of breeding ground activity. It is therefore conceivable to suppose that potential mating and conception could occur in colder, high latitude feeding grounds outside of tropical waters. As other high latitude studies suggest, breeding and mating behaviour could extend beyond previously assumed geographical and temporal restrictions (Clark and Clapham 2004, Simon *et al.* 2010, Vu *et al.* 2012, Magnúsdóttir *et al.* 2014). Therefore, it is conceivable to infer that mating activities and conception take place at higher latitudes, including this subarctic feeding ground of northeast Iceland.

4.3 Study Limitations and Remarks

Long term acoustic studies are useful and logistically practical for extended studies on humpback whale vocalization behaviours. However, there are usually compromises for most types of field studies. As light limitations and logistical restrictions were more challenging in this location, no visual observations were directly associated to the singers recorded in Skjálfandi Bay. The behaviour, presence, and identity of the whale are not discernible for the recorded songs. Since one hydrophone was used in this study, it was also not possible to determine the exact location and proximity of singers to the hydrophone. The songs here can only be assumed to be attributed to certain singers based on the patterned successive vocalization of signals analyzed. Thus, it is not possible to determine whether or not the same individuals here are continuously singing for hours at a time, as seen in breeding grounds, or if the shorter songs are being sung by different chorusing individuals. Although the identity of the whales are not known, it is assumed that the analyzed songs emanate from many different whales, based on the nature of the long term recordings and multiple individuals found chorusing in the data. Some observations of interspersed phrases could not be defined where obvious patterns could not be identified or categorized. These unpatterned sounds were usually faint and observed in poor quality files of low signal-to-noise-ratios. It is possible that these sounds could be attributed to social or feeding sounds sometimes heard together along with song vocalizations (Dunlop *et al.* 2007). However, the poor signal to noise ratios could have masked any present and/or underlying patterns, making it difficult to discriminate between unpatterned or 'aberrant' songs and social sounds. These were not analyzed in detail for this study since the analysis focused on describing and detecting the most prevalent song vocalizations and patterns. As

previously discussed, the 10 minute recording limitations sometimes precluded the identification of a start and end to full songs; consequently, defined song sessions were difficult to differentiate. However, results were still strong and consistent enough to recognize the dominant and particular characteristics of songs in this high latitude feeding ground.

5 Conclusions

Prevalent songs described and characterized from the 2011 research period demonstrate that the established levels of structure and organization are comparable with song structure and organization associated to mating grounds. The extensive occurrence of singing activity detected during peak winter mating season recognizes complex breeding ground behaviour displayed at this high latitude, subarctic feeding ground. This marked peak in singing activity coincides with humpback whale conception periods for the North Atlantic, which suggests that Iceland's subarctic feeding grounds could be, and may already be, used for mating and breeding activity. Therefore, these data support that mating behaviour is not restricted to tropical breeding grounds. The behavioural flexibility shown from this study recognizes Skjálfandi Bay as an important year-round habitat for humpback whales.

This research study not only provides a greater insight and understanding of established humpback whales in this area, but also raises questions for further investigation to support the considerations represented by these investigations. Additional studies in this species and location could be used to determine genders during the winter period. The use of biopsy tests with photo identification methods could demonstrate whether both female and male humpback whales are overwintering in this feeding area at the same time. In addition, it would be very interesting to complete a detailed quantitative analyses and comparison of phrase and theme types found in Iceland, to songs from the West Indies and Cape Verde breeding grounds. Existing literature only provides a few published spectrogram examples available for comparison between these areas. However, figures preceding the past decade of research have limited high quality examples constrained to only visual comparative analyses and assumed to be aurally similar. Thus, an extensive, dedicated comparison of song sound files using the same spectrogram analyses software would provide a much better (and less biased) comparison and understanding of songs from the different areas. Comparisons of pattern sequences, completed by Garland *et al.* (2013b), could also be used to differentiate Iceland's feeding ground population from those heard in West Indies and Cape Verde, using the shifting themes and phrases. Associations and differentiations could further ascertain from which breeding ground this population is most likely associated with.

This thesis research study indicates a more complex and interesting natural history of this intriguing baleen whale species. The findings here challenge traditionally accepted assumptions and support new acoustic research in this field of study for humpback whales. Continued perseverance in understanding humpback whales at this high latitude feeding ground would unveil further exciting answers for the humpback whales of Iceland.

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Appendix A

Chi Square for Markov analysis

True dependence is not possible, since a phrase cannot follow itself, thus the hypothesis are:

H_0 : the order of the phrases are not quasi-dependent of each other

H_1 : the order of the phrases are quasi-dependent of each other

The chi-square equation used for behaviour-based transition frequency analysis when the behaviour transition matrix contains structural zeros on the diagonal cells.

$$\chi^2 = \frac{\sum (f_{ij} - F_{ij}^{(u)})^2}{F_{ij}^{(u)}} \quad \text{Equation 1}$$

where

f_{ij} = the observed frequencies in the i row and j column.

$F_{ij}^{(u)}$ = the estimated expected frequencies using the iterative procedure.

This is an asymptotic chi-square distribution where:

Degrees of freedom: $(I-1)^2 - I = I^2 - 3I + 1$

Iteration Procedure for calculation Expected Values (u)

The expected values at iteration u are labelled $F_{ij}^{(u)}$ and calculated as follows for i rows and j columns:

Step I. Set $u = 0$ and set:

$$F_{ij}^{(0)} = 1 \text{ if } i \neq j \text{ and } F_{ij}^{(0)} = 0 \text{ if } i = j$$

Step II. Set $u = u + 1$

Step III. Calculate the new estimates of Expected values with the formula:

$$F_{ij}^{(2u-1)} = \frac{F_{ij}^{(2u-2)} f_i^A}{\sum F_{ik}^{(2u-2)}} = \frac{F_{ij}^{(2u-2)} f_i^A}{F_i^{A(2u-2)}}$$

where $F_i^{A(2u-2)}$ is the estimated expected frequency in the i^{th} row, determined at Step II.

Step IV. Calculate new estimates of the expected values of values with the formula:

$$F_{ij}^{(2u)} = \frac{F_{ij}^{(2u-1)} f_j^B}{\sum F_{jk}^{(2u-1)}} = \frac{F_{ij}^{(2u-1)} f_j^B}{F_j^{B(2u-2)}}$$

where $F_j^{B(2u-2)}$ is the estimated expected frequency in the j^{th} column, determined at with $2u-1$ (Step III).

Step V. When all the estimated expected values have stabilised (remain essentially unchanged) from those determined in the previous step, these estimates are used as the expected frequencies in Equation 1.

Calculate the new estimates. Iteration process was calculated in R program.

“WhaleScript_chiTest.R”

1) Matrix with 15 traits (Mod Vers 2).

Table A-1. Observed table of frequencies (from Column to Row, ie. From a to b occurred 44 times):

	A	B	C	D	F	G	J	K	L	M	N	O	P	W	X
A	0	44	0	1	1	0	0	5	0	0	0	0	0	0	0
B	0	0	0	76	3	0	0	2	0	0	0	0	0	0	23
C	4	0	0	0	2	0	0	0	0	0	0	0	0	0	0
D	0	0	0	0	0	0	42	0	0	0	0	0	0	0	18
F	31	11	1	0	0	0	0	0	0	0	0	0	0	0	0
G	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
J	0	0	0	0	0	1	0	0	44	0	0	0	0	0	0
K	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0
L	0	0	0	0	1	0	0	0	0	10	0	9	1	0	0
M	0	0	0	0	1	0	0	0	0	0	1	6	0	0	0
N	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
O	0	0	0	0	13	0	0	0	0	0	0	0	0	0	0
P	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
W	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
X	0	0	0	0	0	0	44	0	0	0	0	0	0	0	0

Table A-2. *Expected Table of Frequencies calculated. Final estimated and calculated expected values that stabilized to the 2nd decimal place:*

	A	B	C	D	F	G	J	K	L	M	N	O	P	W	X
A	0	10.4	0.12	10.5 2	3.19	0.12	11.2 7	0.95	5.35	1.18	0.12	2.02	0.12	0	5.66
B	10.5 3	0	0.27	24.2 2	7.35	0.27	25.9 3	2.18	12.3 1	2.71	0.27	4.66	0.27	0	13.0 4
C	0.5	1.12	0	1.14	0.35	0.01	1.22	0.1	0.58	0.13	0.01	0.22	0.01	0	0.61
D	6.09	13.8 5	0.16	0	4.25	0.15	15	1.26	7.12	1.57	0.15	2.69	0.16	0	7.54
F	3.76	8.54	0.1	8.64	0	0.1	9.25	0.78	4.39	0.97	0.1	1.66	0.1	0	4.65
G	0.08	0.19	0	0.19	0.06	0	0.2	0.02	0.1	0.02	0	0.04	0	0	0.1
J	4.65	10.5 6	0.12	10.6 9	3.24	0.12	0	0.96	5.43	1.19	0.12	2.05	0.12	0	5.75
K	0.92	2.09	0.02	2.12	0.64	0.02	2.27	0	1.08	0.24	0.02	0.41	0.02	0	1.14
L	1.91	4.35	0.05	4.4	1.34	0.05	4.71	0.4	0	0.49	0.05	0.85	0.05	0	2.37
M	0.67	1.53	0.02	1.55	0.47	0.02	1.66	0.14	0.79	0	0.02	0.3	0.02	0	0.83
N	0.17	0.37	0	0.38	0.12	0	0.41	0.03	0.19	0.04	0	0.07	0	0	0.2
O	1.11	2.52	0.03	2.55	0.78	0.03	2.73	0.23	1.3	0.29	0.03	0	0.03	0	1.38
P	0.33	0.75	0.01	0.76	0.23	0.01	0.81	0.07	0.39	0.08	0.01	0.15	0	0	0.41
W	0.25	0.56	0.01	0.57	0.17	0.01	0.61	0.05	0.29	0.06	0.01	0.11	0.01	0	0.31
X	4.03	9.17	0.1	9.28	2.82	0.1	9.93	0.83	4.71	1.04	0.1	1.78	0.1	0	0

Using R program with *chisquare {stats} package*:

Equation 1:

$$\chi^2 = (\text{Table A "Observed Values"}) - (\text{Table B "Estimated Expected Values"}) = 2095.226$$

Degrees of freedom: $(15)^2 - (3 \times 15) + 1 = 181$

Chi square critical value calculated with P value = 0.05:

`qchisq(0.95,181)`

$$\chi^2 = 213.3906$$

Chi square critical value calculated with P value = 0.001:

`qchisq(0.999,181)`

$$\chi^2 = 245.533$$

The $P < 0.001$ and H_0 is rejected (H_0 : the order of the phrases are not quasi-dependent of each other). Therefore, the order of the phrases *is sequentially dependent* of each other and *not quasi-independent*.

II) Matrix with 9 traits (Mod Vers 3)

Table A-3. *Observed Table of Frequencies.*

	A	B	D	F	J	K	L	O	X
A	0	44	1	1	0	5	0	0	0
B	0	0	76	3	0	2	0	0	23
D	0	0	0	0	42	0	0	0	18
F	31	11	0	0	0	0	0	0	0
J	0	0	0	0	0	0	44	0	0
K	0	11	0	0	0	0	0	0	0
L	0	0	0	1	0	0	0	9	0
O	0	0	0	13	0	0	0	0	0
X	0	0	0	0	44	0	0	0	0

Table A-4. Expected Table of Frequencies calculated (final estimated expected values that stabilized to the 2nd decimal place):

	A	B	D	F	J	K	L	O	X
A	0	11.57	11.47	2.47	12.18	0.89	5.58	1.15	5.7
B	10.39	0	27.22	5.86	28.91	2.11	13.25	2.72	13.53
D	5.98	15.8	0	3.38	16.64	1.21	7.63	1.57	7.79
F	3.48	9.18	9.1	0	9.67	0.71	4.43	0.91	4.52
J	4.46	11.78	11.68	2.52	0	0.9	5.69	1.17	5.8
K	0.88	2.33	2.32	0.5	2.46	0	1.13	0.23	1.15
L	0.88	2.32	2.3	0.5	2.45	0.18	0	0.23	1.14
O	1.05	2.77	2.75	0.59	2.92	0.21	1.34	0	1.37
X	3.88	10.24	10.16	2.19	10.79	0.79	4.95	1.02	0

Using R program with *chisquare {stats}*:

Equation 1:

$$\chi^2 = (\text{Table A "Observed Values"}) - (\text{Table B "Estimated Expected Values"}) = 1720.807$$

Degrees of freedom: $(9)^2 - (3 \times 9) + 1 = 55$

Chi square critical value calculated with P value = 0.05:

Qchisq (0.95,55)

$$\chi^2 = 73.31149$$

Chi square critical value calculated with P value = 0.001:

qchisq(0.999,55)

$$\chi^2 = 93.16753$$

The $P < 0.001$ and H_0 is rejected (H_0 : the order of the phrases are not quasi-dependent of each other). Therefore, the order of the phrases are sequentially dependent of each other and not quasi-independent.

III) Matrix with 6 traits (Mod Vers 4)

Table A-5. Observed Table of Frequencies

	A	B	D	F	J	X
1	A	0	44	1	1	0
2	B	0	0	76	3	0
3	D	0	0	0	0	42
4	F	31	11	0	0	0
5	J	0	0	0	0	0
6	X	0	0	0	0	44

Table A-6. Expected Table of Frequencies calculated (final estimated expected values that stabilized to the 2nd decimal place):

	A	B	D	F	J	X	
1	A	0	12.37	14.11	0.64	12.15	6.73
2	B	13.43	0	37.16	1.69	31.99	17.74
3	D	8.27	20.06	0	1.04	19.7	10.92
4	F	4.24	10.3	11.74	0	10.11	5.61
5	J	0	0	0	0	0	0
6	X	5.06	12.27	13.99	0.63	12.05	0

Using R program with chisquare {stats}:

Equation 1:

$$\chi^2 = (\text{Table A "Observed Values"}) - (\text{Table B "Estimated Expected Values"}) = 572.998$$

Degrees of freedom: $(6)^2 - (3*6) + 1 = 19$

Chi square critical value calculated with P value = 0.05:

qchisq(0.95,19)

$$\chi^2 = 30.14353$$

Chi square critical value calculated with P value = 0.001:

qchisq(0.999,55)

$$\chi^2 = 43.8202$$

The $P < 0.001$ and H_0 is rejected (H_0 : the order of the phrases are not quasi-dependent of each other). Therefore, the order of the phrases are sequentially dependent of each other and not quasi-independent.

Appendix B

Table B-1. *The total number of detections counted per day along with the total number of wav files analyzed per day.*

Date	Detections	Wav files	Date	Detections	Wav files
26-Jan	71	2	01-Mar	774	3
27-Jan	599	6	02-Mar	2434	4
28-Jan	165	3	03-Mar	703	0
29-Jan	485	6	04-Mar	1896	2
30-Jan	12123	4	05-Mar	1116	4
31-Jan	4978	4	06-Mar	2981	1
01-Feb	780	4	07-Mar	2024	1
02-Feb	3743	4	08-Mar	2787	5
03-Feb	1092	4	09-Mar	2975	1
04-Feb	1220	4	10-Mar	1410	0
05-Feb	5807	6	11-Mar	12649	4
06-Feb	8508	4	12-Mar	6176	3
07-Feb	6434	3	Total	365994	151
08-Feb	999	1			
09-Feb	10765	4			
10-Feb	3332	4			
11-Feb	11057	3			
12-Feb	18769	4			
13-Feb	26560	5			
14-Feb	12356	4			
15-Feb	23743	4			
16-Feb	28372	3			
17-Feb	18949	4			
18-Feb	16180	5			
19-Feb	20697	5			
20-Feb	18191	4			
21-Feb	13690	3			
22-Feb	11634	2			
23-Feb	11803	4			
24-Feb	15789	4			
25-Feb	10460	4			
26-Feb	4000	2			
27-Feb	3642	0			
28-Feb	1076	0			

Appendix C

Is there a difference or similarity between the different phrase type durations (*ie. Comparing Phrase a with Phrase b*)?

- H_0 : There are no differences between the different phrase type's durations
- H_1 : There are differences between the different phrase types's durations

Kruskal-Wallis Test

Test homogeneity of variance (using R program: `bartlett.test {stats}`)

Note that the Y phrase duration of 37.1 was not included here as Bartlett's Test requires at least 2 observations from each group.

Bartlett Test (0.05 as critical level)

Bartlett's K-squared = 233.3371, df = 18, p-value < 2.2e-16

The Bartlett test showed that the p value is significantly smaller than $P = 0.05$ therefore we reject the H_0 (null hypothesis) and cannot assume homogeneity of variances. I chose to use a non-parametric statistic test (Kruskal-Wallis) instead of ANOVA. This is because One-way ANOVA assumes that the data come from populations that are normally distributed and have equal variances which are not satisfied here.

- H_0 : There are no differences between the phrase group's durations
- H_1 : There are differences between the phrase group's durations

Kruskal-Wallis rank sum test results in R program: `kruskal.test {stats}`

Without assuming the data to have normal distribution, test at 0.05 significance level if the phrase groups have differences between phrase durations.

The null hypothesis is that there is no difference between the phrase durations. To test the hypothesis, I apply the `kruskal.test` function to compare the independent phrase groups. The p-value turns out to be (2.2e-16).

Hence I reject the null hypothesis, and conclude that there are differences between the phrase group's durations.

Kruskal-Wallis rank sum test

Kruskal-Wallis chi-squared = 385.2847, df = 18, p-value < 2.2e-16

Using P value 0.05:
[1] 28.8693

Using P value 0.01
[1] 34.80531

Using P value 0.001
[1] 42.3124

Multiple comparisons between treatments

A Multiple Comparisons between treatments test was completed to show which groups are different.

- H_0 : Group u and v are similar
- H_1 : Group u and v are not similar

A Multiple Comparisons between treatments test was completed to show that there were significant differences (higher observed value than the critical value).

Multiple comparison test after Kruskal-Wallis in R program:

p.value: 0.05							
Compar.	obs.dif	critical.dif	differ				
A-B	225.992889	158.78805	TRUE	D-J	149.230924	288.32528	FALSE
A-C	221.299419	504.19914	FALSE	D-Jfast	398.500000	482.26684	FALSE
A-D	110.658915	314.90089	FALSE	D-K	71.416667	482.26684	FALSE
A-F	29.909578	160.88359	FALSE	D-L	303.014368	305.88755	FALSE
A-F2	43.992248	575.97211	FALSE	D-M	379.410256	336.61378	TRUE
A-G	367.986919	211.88110	TRUE	D-N	166.208333	440.24738	FALSE
A-I	295.424419	697.70916	FALSE	D-O	232.933333	329.45097	FALSE
A-J	38.572009	165.04496	FALSE	D-O2	323.166667	393.76922	FALSE
A-Jfast	287.841085	420.34471	FALSE	D-P	436.833333	622.60381	FALSE
A-K	39.242248	420.34471	FALSE	D-W	348.416667	736.67476	FALSE
A-L	192.355453	194.10193	FALSE	D-X	149.871212	346.14247	FALSE
A-M	268.751342	239.61888	TRUE	F-F2	73.901826	560.67501	FALSE
A-N	55.549419	371.38406	FALSE	F-G	338.077340	165.84990	TRUE
A-O	122.274419	229.44784	FALSE	F-I	265.514840	685.13551	FALSE
A-O2	212.507752	314.90089	FALSE	F-J	8.662431	99.25940	FALSE
A-P	326.174419	575.97211	FALSE	F-Jfast	257.931507	399.12687	FALSE
A-W	459.075581	697.70916	FALSE	F-K	69.151826	399.12687	FALSE
A-X	260.530127	252.82994	TRUE	F-L	162.445875	142.43648	TRUE
B-C	447.292308	485.96242	FALSE	F-M	238.841763	200.07448	TRUE
B-D	115.333974	284.78988	FALSE	F-N	25.639840	347.18685	FALSE
B-F	255.902468	88.46601	TRUE	F-O	92.364840	187.77354	FALSE
B-F2	182.000641	560.07730	FALSE	F-O2	182.598174	285.96357	FALSE
B-G	593.979808	163.81790	TRUE	F-P	296.264840	560.67501	FALSE
B-I	521.417308	684.64646	FALSE	F-W	488.985160	685.13551	FALSE
B-J	264.564898	95.82558	TRUE	F-X	290.439705	215.72105	TRUE
B-Jfast	513.833974	398.28680	TRUE	F2-G	411.979167	577.37902	FALSE
B-K	186.750641	398.28680	FALSE	F2-I	339.416667	880.49475	FALSE
B-L	418.348342	140.06521	TRUE	F2-J	82.564257	561.88324	FALSE
B-M	494.744231	198.39333	TRUE	F2-Jfast	331.833333	682.02830	FALSE
B-N	281.542308	346.22077	FALSE	F2-K	4.750000	682.02830	FALSE
B-O	348.267308	185.98122	TRUE	F2-L	236.347701	571.09412	FALSE
B-O2	438.500641	284.78988	TRUE	F2-M	312.743590	588.12426	FALSE
B-P	552.167308	560.07730	FALSE	F2-N	99.541667	652.99238	FALSE
B-W	233.082692	684.64646	FALSE	F2-O	166.266667	584.05414	FALSE
B-X	34.537238	214.16275	FALSE	F2-O2	256.500000	622.60381	FALSE
C-D	331.958333	556.87378	FALSE	F2-P	370.166667	787.53845	FALSE
C-F	191.389840	486.65117	FALSE	F2-W	415.083333	880.49475	FALSE
C-F2	265.291667	736.67476	FALSE	F2-X	216.537879	593.62944	FALSE
C-G	146.687500	505.80573	FALSE	G-I	72.562500	698.87104	FALSE
C-I	74.125000	835.31066	FALSE	G-J	329.414910	169.88967	TRUE
C-J	182.727410	488.04269	FALSE	G-Jfast	80.145833	422.27045	FALSE
C-Jfast	66.541667	622.60381	FALSE	G-K	407.229167	422.27045	FALSE
C-K	260.541667	622.60381	FALSE	G-L	175.631466	198.23779	FALSE
C-L	28.943966	498.61949	FALSE	G-M	99.235577	242.98121	FALSE
C-M	47.451923	518.03768	FALSE	G-N	312.437500	373.56229	FALSE
C-N	165.750000	590.65384	FALSE	G-O	245.712500	232.95701	TRUE
C-O	99.025000	513.41225	FALSE	G-O2	155.479167	317.46690	FALSE
C-O2	8.791667	556.87378	FALSE	G-P	41.812500	577.37902	FALSE
				G-W	827.062500	698.87104	TRUE
				G-X	628.517045	256.01883	TRUE

C-P	104.875000	736.67476	FALSE	I-J	256.852410	686.12460	FALSE
C-W	680.375000	835.31066	FALSE	I-Jfast	7.583333	787.53845	FALSE
C-X	481.829545	524.27933	FALSE	I-K	334.666667	787.53845	FALSE
D-F	140.568493	285.96357	FALSE	I-L	103.068966	693.68775	FALSE
D-F2	66.666667	622.60381	FALSE	I-M	26.673077	707.77422	FALSE
D-G	478.645833	317.46690	TRUE	I-N	239.875000	762.53082	FALSE
D-I	406.083333	736.67476	FALSE	I-O	173.150000	704.39580	FALSE
				I-O2	82.916667	736.67476	FALSE
I-P	30.750000	880.49475	FALSE	K-X	221.287879	444.23160	FALSE
I-W	754.500000	964.53367	FALSE	L-M	76.395889	227.64408	FALSE
I-X	555.954545	712.35533	FALSE	L-N	136.806034	363.77292	FALSE
J-Jfast	249.269076	400.82237	FALSE	L-O	70.081034	216.91226	FALSE
J-K	77.814257	400.82237	FALSE	L-O2	20.152299	305.88755	FALSE
J-L	153.783444	147.12056	TRUE	L-P	133.818966	571.09412	FALSE
J-M	230.179333	203.43576	TRUE	L-W	651.431034	693.68775	FALSE
J-N	16.977410	349.13467	FALSE	L-X	452.885580	241.51107	TRUE
J-O	83.702410	191.35101	FALSE	M-N	213.201923	389.96460	FALSE
J-O2	173.935743	288.32528	FALSE	M-O	146.476923	258.44260	FALSE
J-P	287.602410	561.88324	FALSE	M-O2	56.243590	336.61378	FALSE
J-W	497.647590	686.12460	FALSE	M-P	57.423077	588.12426	FALSE
J-X	299.102136	218.84213	TRUE	M-W	727.826923	707.77422	TRUE
Jfast-K	327.083333	556.87378	FALSE	M-X	529.281469	279.40875	TRUE
Jfast-L	95.485632	413.63546	FALSE	N-O	66.725000	383.79876	FALSE
Jfast-M	19.089744	436.84773	FALSE	N-O2	156.958333	440.24738	FALSE
Jfast-N	232.291667	520.90772	FALSE	N-P	270.625000	652.99238	FALSE
Jfast-O	165.566667	431.35257	FALSE	N-W	514.625000	762.53082	FALSE
Jfast-O2	75.333333	482.26684	FALSE	N-X	316.079545	398.21873	FALSE
Jfast-P	38.333333	682.02830	FALSE	O-O2	90.233333	329.45097	FALSE
Jfast-W	746.916667	787.53845	FALSE	O-P	203.900000	584.05414	FALSE
Jfast-X	548.371212	444.23160	TRUE	O-W	581.350000	704.39580	FALSE
K-L	231.597701	413.63546	FALSE	O-X	382.804545	270.73668	TRUE
K-M	307.993590	436.84773	FALSE	O2-P	113.666667	622.60381	FALSE
K-N	94.791667	520.90772	FALSE	O2-W	671.583333	736.67476	FALSE
K-O	161.516667	431.35257	FALSE	O2-X	473.037879	346.14247	TRUE
K-O2	251.750000	482.26684	FALSE	P-W	785.250000	880.49475	FALSE
K-P	365.416667	682.02830	FALSE	P-X	586.704545	593.62944	FALSE
K-W	419.833333	787.53845	FALSE	W-X	198.545455	712.35533	FALSE

As an additional measure, ANOVA results were also tested.

ANOVA Results from R:

Terms:

```

              categ Residuals
Sum of Squares 33573.46  66701.44
Deg. of Freedom      18      903

```

Residual standard error: 8.594561
Estimated effects may be unbalanced

```

> summary(aov(as.numeric(unlist(dati)) ~ categ))
Df Sum Sq Mean Sq F value Pr(>F)
categ      18   33573   1865.2    25.25 <2e-16 ***
Residuals   903   66701     73.9
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```

ANOVA reveals a significant variability among the phrase durations. Since the p-value of 2e-16 is smaller than the .05 significance level, we reject the H_0 (null hypothesis) that there is no difference in the Phrase Durations.

Appendix D

PHRASE GROUP DURATIONS BY GROUP (Even sample sizes)

- H_0 : There are no durational differences within a phrase type's groups
- H_1 : There are durational differences within a phrase type's groups

Phrases By Period (using the highest frequencies of Phrase Count data from the summary table (total of 9 Phrase Groups out of 20 Phrase Types analysed)).

Using P value = 0.05

Bonferroni Correction P value: $0.05 / 9 = 0.0055$

SUMMARY

Significant Reject H_0	Not Significant Accept H_0
Phrase B – Kruskal Wallis Test	Phrase A – Kruskal Wallis Test
Phrase F – Kruskal Wallis Test	Phrase G – Kruskal Wallis Test – homogenous but not normally distributed
Phrase L – ANOVA & Kruskal Wallis Test	Phrase J – ANOVA & Kruskal Wallis Test
	Phrase M – Kruskal Wallis – homogenous but not normally distributed
	Phrase O – Kruskal Wallis Test
	Phrase X – ANOVA & Kruskal Wallis Test

Phrase A

Period	Count (total=43)
Period 1	n=14
Period 2	n=14
Period 3	n=15

BARTLETT TEST OF HOMOGENEITY OF VARIANCES

Bartlett's K-squared = 7.806, df = 2, p-value = 0.02018

The p value (0.02018) is smaller than 0.05 thus we reject the H_0 and cannot assume homogeneity of variances.

KRUSKAL-WALLIS RANK SUM TEST

kruskal.test(dati)

Kruskal-Wallis chi-squared = 2.2097, df = 2, p-value = 0.3313

The p value (0.3313) is larger than 0.05 thus we accept the H_0 (null hypothesis) and conclude that there is no difference between the Phrase group durations.

MULTIPLE COMPARISON TEST AFTER KRUSKAL-WALLIS

p.value: 0.05

Comparisons

	obs.dif	critical.dif	difference
A1-A2	6.4285714	11.36165	FALSE
A1-A3	0.7571429	11.17068	FALSE
A2-A3	5.6714286	11.17068	FALSE

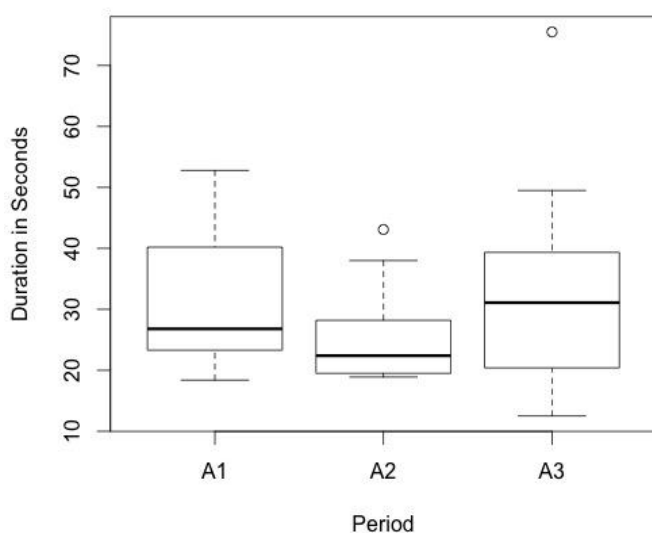


Figure D-1. Boxplot of Phrase A durations by period.

Phrase B

Period	Count (total=260)
Period 1	n=87
Period 2	n=87
Period 3	n=86

BARTLETT TEST OF HOMOGENEITY OF VARIANCES

Bartlett's K-squared = 70.7951, df = 2, p-value = 4.237e-16

The p value of (4.237e-16) is smaller than 0.05 thus we reject the H0 and cannot assume homogeneity of variances.

KRUSKAL-WALLIS RANK SUM TEST

Kruskal-Wallis chi-squared = 28.0218, df = 2, p-value = 8.225e-07

Kruskal-Wallis Test showed that the p value (8.225e-07) was less than 0.05, thus we rejected the H₀ and conclude that there are differences between the Phrase period's durations. The MC post-hoc test showed that Phrase Group B3 differs from and B1 and B2.

MULTIPLE COMPARISON TEST AFTER KRUSKAL-WALLIS

p.value: 0.05

Comparisons

obs.dif critical.dif difference

B1-B2 10.07471 27.29557 FALSE

B1-B3 56.77152 27.37480 TRUE

B2-B3 46.69681 27.37480 TRUE

PAIRWISE COMPARISONS USING WILCOXON RANK SUM TEST

B1 B2

B2 1.00000 -

B3 1.6e-06 0.00017

P value adjustment method: bonferroni

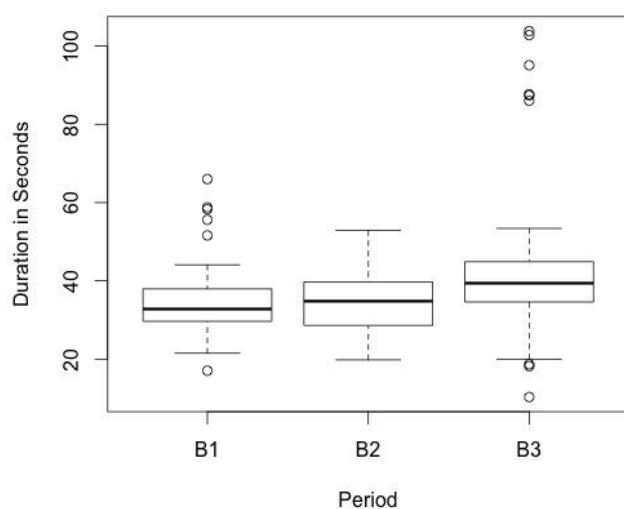


Figure D-2. Boxplot of Phrase B durations by period.

Phrase F

Period	Count (total=219)
Period 1	n=73
Period 2	n=73
Period 3	n=73

BARTLETT TEST OF HOMOGENEITY OF VARIANCES

Bartlett's K-squared = 15.7986, df = 2, p-value = 0.000371

The p value of (**0.000371**) is smaller than 0.05 thus we reject the H0 and cannot assume homogeneity of variances.

KRUSKAL-WALLIS RANK SUM TEST

Kruskal-Wallis chi-squared = 23.1921, df = 2, p-value = 9.202e-06

Kruskal-Wallis Test showed that the p value (9.202e-06) was less than 0.05, thus we rejected the H₀ and conclude that there are differences between the Phrase group durations. The MC post-hoc test showed that Phrase Group F2 differs from and F1 and F3.

MULTIPLE COMPARISON TEST AFTER KRUSKAL-WALLIS

p.value: 0.05

Comparisons

	obs.dif	critical.dif	difference
F1-F2	34.46575	25.10827	TRUE
F1-F3	14.73973	25.10827	FALSE
F2-F3	49.20548	25.10827	TRUE

PAIRWISE COMPARISONS USING WILCOXON RANK SUM TEST

F1 F2

F2 0.003 -

F3 0.473 8.9e-06

P value adjustment method: bonferroni

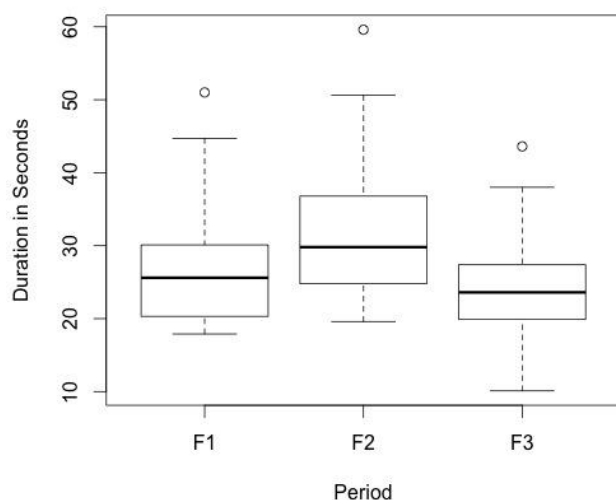


Figure D-3. Boxplot of Phrase F durations by period.

Phrase G

Period	Count (total=40)
Period 1	n=13
Period 2	n=13
Period 3	n=14

BARTLETT TEST OF HOMOGENEITY OF VARIANCES

Bartlett's K-squared = 2.1912, df = 2, p-value = 0.3343

The p value of (p-value = 0.3343) is larger than 0.05 thus we accept the H_0 and can assume homogeneity of variances.

SHAPIRO-WILK NORMALITY TEST

data: log(as.numeric(unlist(dati)))
W = 0.7841, p-value = 3.204e-06

The p value of (3.204e-06) is smaller than 0.05 thus we reject the H_0 and cannot assume normality. Therefore a Kruskal Wallis test is applied.

KRUSKAL-WALLIS RANK SUM TEST

Kruskal-Wallis chi-squared = 1.3574, df = 2, p-value = 0.5073

The p value (0.5073) is larger than 0.05 thus we accept the null hypothesis and conclude that there is no difference between the phrase group durations.

Multiple comparison test after Kruskal-Wallis (extra check)

p.value: 0.05

Comparisons

obs.dif critical.dif difference

G1-G2 4.8846154 10.97729 FALSE

G1-G3 0.6291209 10.77948 FALSE

G2-G3 4.2554945 10.77948 FALSE

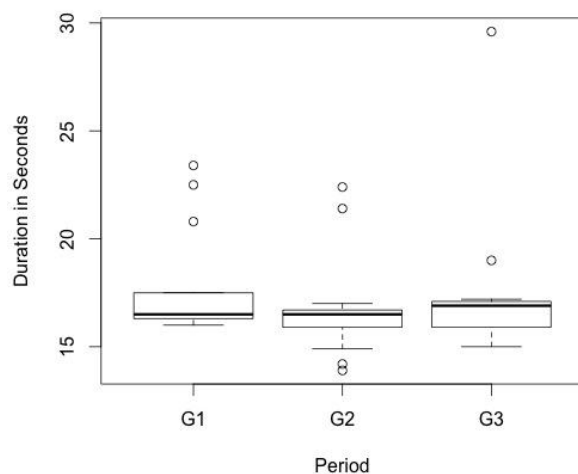


Figure D-4. Boxplot of Phrase G durations by period.

Phrase J

Period	Count (total=166)
Period 1	n=55
Period 2	n=55
Period 3	n=56

BARTLETT TEST OF HOMOGENEITY OF VARIANCES

Bartlett's K-squared = 4.0122, df = 2, p-value = 0.1345

The p value (0.1345) is larger than 0.05 thus we accept the H_0 and can assume homogeneity of variances.

SHAPIRO-WILK NORMALITY TEST

W = 0.9933, p-value = 0.6401

Accept H_0 and it is Normal – try ANOVA

The p value of (0.6401) is larger than 0.05 thus we accept the H_0 and can assume normality. Therefore an ANOVA test is applied.

ANOVA

```
      categ Residuals
Sum of Squares  0.083534  6.303324
Deg. of Freedom    2    163
```

Residual standard error: 0.1966487
Estimated effects may be unbalanced

```
summary(aov(log(as.numeric(unlist(dati))) ~ categ))
      Df Sum Sq Mean Sq F value Pr(>F)
categ    2  0.084  0.04177   1.08  0.342
Residuals 163  6.303  0.03867
```

The p value (0.342) is larger than 0.05 thus we accept the null hypothesis and conclude that there is no difference between phrase group period durations. *Note: A Kruskal Wallis test was also applied to provide an additional test that gave a p value (0.1818) - which agreed with the ANOVA test.*

KRUSKAL-WALLIS RANK SUM TEST (in addition)

Kruskal-Wallis chi-squared = 3.4101, df = 2, p-value = 0.1818

The p value (0.1818) is larger than 0.05 thus we accept the null hypothesis and conclude that there is no difference between phrase group period durations.

Multiple comparison test after Kruskal-Wallis

p.value: 0.05

Comparisons

```
      obs.dif critical.dif difference
J1-J2 16.890909  21.94198  FALSE
J1-J3  9.361688  21.84380  FALSE
J2-J3  7.529221  21.84380  FALSE
```

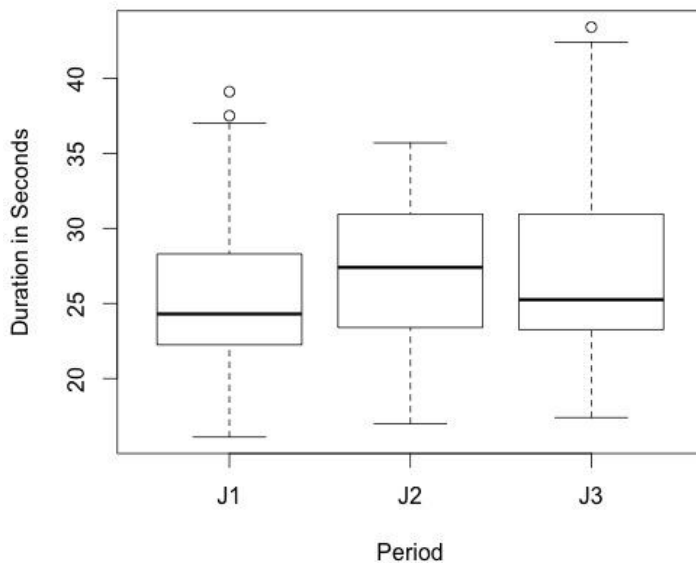



Figure D-5. Boxplot of Phrase J durations by period.

Phrase L

Period	Count (total=58)
Period 1	n=19
Period 2	n=19
Period 3	n=20

Bartlett test of homogeneity of variances

Bartlett's K-squared = 4.9629, df = 2, p-value = 0.08362

The p value of (0.9289) is larger than 0.05 thus we accept the H_0 and assume homogeneity of variances.

Shapiro-Wilk normality test

data: log(as.numeric(unlist(dati)))

W = 0.9775, p-value = 0.354

The p value (0.354) is larger than 0.05 thus we accept the H_0 and can assume normality. Therefore we use ANOVA.

ANOVA

```
      categ Residuals
Sum of Squares 0.5781956 2.4916290
Deg. of Freedom    2    55
```

Residual standard error: 0.2128435
Estimated effects may be unbalanced

```
summary(aov(log(as.numeric(unlist(dati))) ~ categ))
      Df Sum Sq Mean Sq F value Pr(>F)
categ    2 0.5782  0.2891   6.382 0.00322 **
Residuals 55 2.4916  0.0453
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

The p value (0.00322) is larger than 0.05 thus we accept the null hypothesis and conclude that there is no difference between phrase group period durations.

Note: A Kruskal Wallis test was also applied to provide an additional test that gave a p value (0.004016) - which agreed with the ANOVA test.

Pairwise comparisons using t tests with pooled SD

```
  L1  L2
L2 0.0132 -
L3 1.0000 0.0065
P value adjustment method: bonferroni
```

Kruskal-Wallis rank sum test

Kruskal-Wallis chi-squared = 11.0348, df = 2, p-value = 0.004016

Multiple comparison test after Kruskal-Wallis

```
p.value: 0.05
Comparisons
      obs.dif critical.dif difference
L1-L2 15.052632   13.11620    TRUE
L1-L3  1.173684   12.95121    FALSE
L2-L3 16.226316   12.95121    TRUE
```

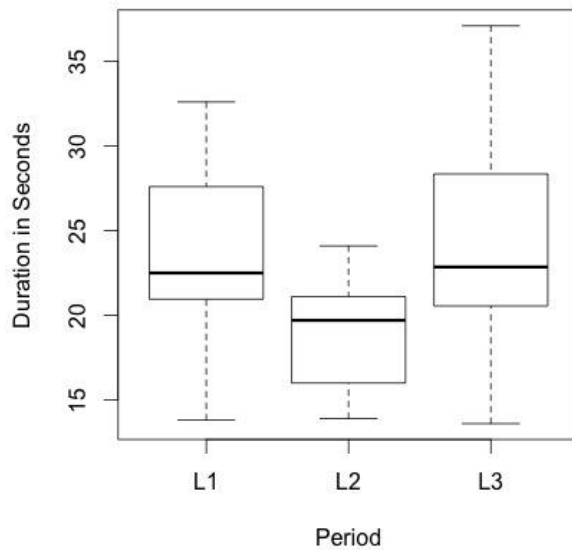


Figure D-6. Boxplot of Phrase L durations by period.

Phrase M

Period	Count (total=26)
Period 1	n=9
Period 2	n=9
Period 3	n=8

BARTLETT TEST OF HOMOGENEITY OF VARIANCES

Bartlett's K-squared = 0.1262, df = 2, p-value = 0.9388

The p value (0.9388) is larger than 0.05 thus we accept the H_0 and assume homogeneity of variances.

SHAPIRO-WILK NORMALITY TEST

data: log(as.numeric(unlist(dati)))
W = 0.8545, p-value = 0.001738

The p value of (0.001738) is smaller than 0.05 thus we reject the H_0 and cannot assume normality. Therefore a Kruskal Wallis test is applied.

KRUSKAL-WALLIS RANK SUM TEST

Kruskal-Wallis chi-squared = 3.5075, df = 2, p-value = 0.1731

KW Test showed that the p value was less than 0.05, thus we rejected the H_0 and conclude that there are differences between the phrase group period durations.

```
qchisq(0.950,kruskal.test(dati)$parameter)
[1] 3.841459
```

MULTIPLE COMPARISON TEST AFTER KRUSKAL-WALLIS

p.value: 0.05

Comparisons

	obs.dif	critical.dif	difference
M1-M2	0.7222222	8.631617	FALSE
M1-M3	6.4097222	8.897267	FALSE
M2-M3	5.6875000	8.897267	FALSE

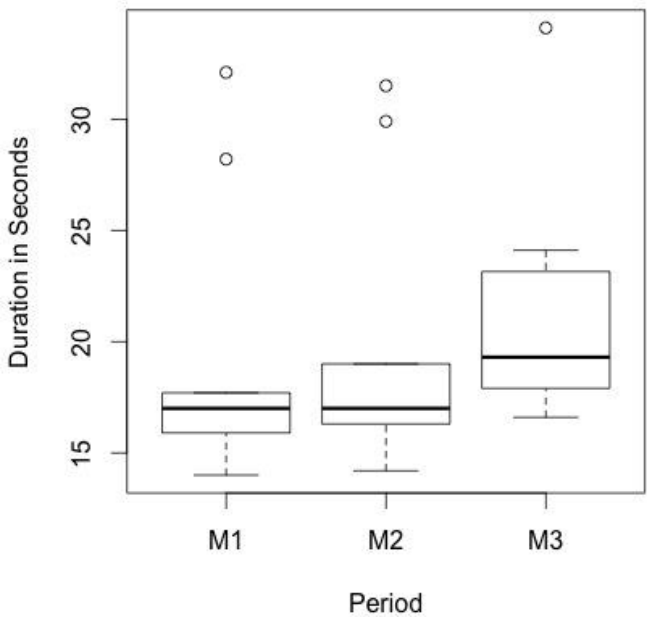


Figure D-7. Boxplot of Phrase M durations by period

Phrase 0

Period	Count (total=30)
Period 1	n=10
Period 2	n=10
Period 3	n=10

BARTLETT TEST OF HOMOGENEITY OF VARIANCES

Bartlett's K-squared = 17.724, df = 2, p-value = 0.0001417

The p value of (0.0001417) is smaller than 0.05 thus we reject the H0 and cannot assume homogeneity of variances.

KRUSKAL-WALLIS RANK SUM TEST

Kruskal-Wallis chi-squared = 1.2166, df = 2, p-value = 0.5443

The p value (0.5443) is larger than 0.05 thus we accept the null hypothesis and conclude that there is no difference between phrase group period durations.

Multiple comparison test after Kruskal-Wallis (additional check)

p.value: 0.05

Comparisons

	obs.dif	critical.dif	difference
01-02	0.3	9.425108	FALSE
01-03	3.9	9.425108	FALSE
02-03	3.6	9.425108	FALSE

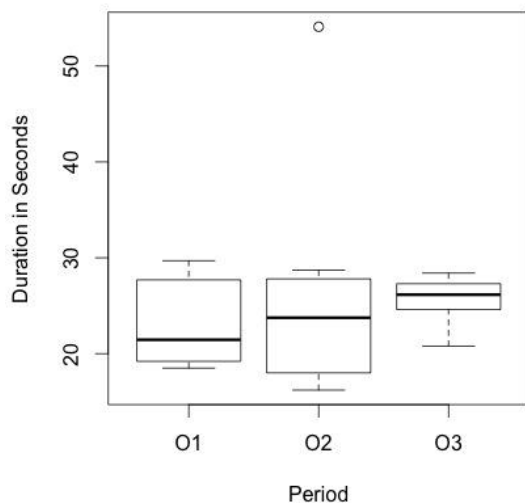


Figure D-8. Boxplot of Phrase 0 durations by period.

Phrase X

Period	Count (total=22)
Period 1	n=7
Period 2	n=7
Period 3	n=8

BARTLETT TEST OF HOMOGENEITY OF VARIANCES

Bartlett's K-squared = 0.2218, df = 2, p-value = 0.895

The p value (0.895) is larger than 0.05 thus we accept the H_0 and assume homogeneity of variances.

SHAPIRO-WILK NORMALITY TEST

data: log(as.numeric(unlist(dati)))
W = 0.947, p-value = 0.2747

The p value of (0.2747) is larger than 0.05 thus we accept the H_0 and can assume normality. Therefore an ANOVA test is applied.

Kruskal-Wallis rank sum test

data: dati
Kruskal-Wallis chi-squared = 1.3623, df = 2, p-value = 0.506

ONE-WAY ANALYSIS OF VARIANCE (USING LOG TRANSFORMED DATA)

Call:
aov(formula = log(as.numeric(unlist(dati))) ~ categ)

Terms:
categ Residuals
Sum of Squares 0.0284583 0.4133135
Deg. of Freedom 2 19

Residual standard error: 0.1474902
Estimated effects may be unbalanced

```
> summary(aov(log(as.numeric(unlist(dati))) ~ categ))
      Df Sum Sq Mean Sq F value Pr(>F)
categ    2  0.0285  0.01423   0.654  0.531
Residuals 19  0.4133  0.02175
```

The p value (0.531) is larger than 0.05 thus we accept the null hypothesis and conclude that there is no difference between phrase group period durations.

Note: A Kruskal Wallis test was also applied to provide an additional test that gave a p value (0.05755) - which agreed with the ANOVA test.

Pairwise comparisons using t tests with pooled SD - extra check

data: periods and categ
X1 X2
X2 1.00 -
X3 0.91 1.00

P value adjustment method: bonferroni
Multiple comparison test after Kruskal-Wallis (additional check)

p.value: 0.05
Comparisons

	obs.dif	critical.dif	difference
X1-X2	0.4285714	8.309427	FALSE
X1-X3	3.5535714	8.045568	FALSE
X2-X3	3.1250000	8.045568	FALSE

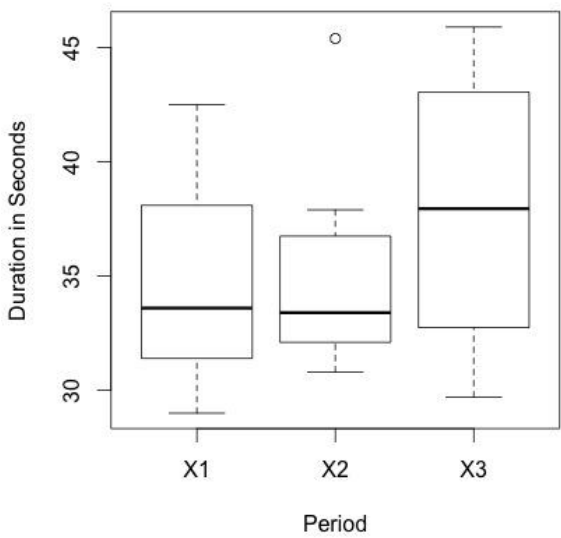


Figure D-9. Boxplot of Phrase X durations by period.

Appendix E

Table E-1. Transition phrase group summary table with durations.

Name	Count (n)	Percent	Average Duration (sec)	Margin of Error (95%)	Median	Max	Min	Standard Deviation (SD)	Coefficient of Variance
Phrase A->B	32	7.21	31.49	4.31	27.90	86.50	19.10	12.44	39.51
Phrase A->K	3	0.68	34.27	7.44	36.00	39.80	27.00	6.57	19.18
Phrase Along->B	2	0.45	42.75	18.52	42.75	52.20	33.30	13.36	31.26
Phrase A Transitions	37		36.17						
Phrase B->D	49	11.04	50.91	5.66	46.00	116.40	21.70	20.20	39.68
Phrase B->F	2	0.45	30.80	15.88	30.80	38.90	22.70	11.46	37.19
Phrase B->K	2	0.45	22.05	11.86	22.05	28.10	16.00	8.56	38.80
Phrase B->X	21	4.73	60.09	5.98	61.50	84.50	29.40	13.98	23.26
Phrase B Transitions	74		40.96						
Phrase C->A	3	0.68	42.83	2.05	43.10	44.50	40.90	1.81	4.24
Phrase C Transitions	3		42.83						
Phrase D->X	6	1.35	36.50	7.70	34.85	51.80	26.90	9.62	26.37
Phrase D->J	36	8.11	32.35	4.12	29.80	88.20	19.60	12.62	39.02
Phrase D Transitions	42		34.43						
Phrase F->A	23	5.18	41.54	8.95	36.30	107.20	12.80	21.89	52.71
Phrase F->B	6	1.35	61.15	26.42	45.40	125.60	40.70	33.01	53.99
Phrase F->F2	9	2.03	32.27	15.59	29.80	88.20	4.12	23.86	73.92
Phrase F2->B	9	2.03	40.50	19.17	36.30	107.20	8.95	29.34	72.46
Phrase F Transitions	47		43.86						
Phrase J->Jfast	4	0.90	19.85	8.74	19.00	30.90	10.50	8.91	44.90
Phrase J->L	39	8.78	17.11	1.15	17.50	27.80	10.30	3.67	21.43
Phrase J Transitions	43		3.48						
Phrase K->B	9	2.03	27.41	3.20	24.70	34.40	22.00	4.90	17.89
Phrase K Transitions	9		27.41						
Phrase L->M	10	2.25	15.89	3.06	15.20	24.60	9.80	4.94	31.10
Phrase L->O	7	1.58	16.90	2.74	18.70	20.30	9.60	3.70	21.87
Phrase L Transitions	17		16.4						

Phrase M->O	5	1.13	19.86	4.91	20.10	26.80	11.20	5.60	28.18
Phrase M Transitions	5		19.86						
Phrase O->F	8	1.80	19.88	4.29	19.95	33.10	12.60	6.19	31.16
Phrase O2->F	3	0.68	19.53	10.09	18.30	29.00	11.30	8.91	45.64
Phrase O Transitions	11		19.53						
Phrase P->F	4	0.90	18.93	11.03	13.50	35.80	12.90	11.26	59.49
Phrase P Transitions	4		18.93						
Phrase X->J	38	8.56	28.32	2.56	27.00	49.10	15.70	8.05	28.43
Phrase X Transitions	38								

Appendix F

Table F-1. *Theme transition summary table.*

Theme Name	Count (n)	No. with Durations	Average Duration (sec)	Max	Min	Standard Deviation (SD)	Coefficient of Variance
Theme A	4	4	123.6	206.7	79.2	58.6	47.4
Theme A-B	6	6	114.5	208.9	66.1	52.1	45.5
Theme A-D	1	1	163.1	NA	NA	NA	NA
Theme A-F	1	1	98.5	NA	NA	NA	NA
Theme A-K-B	2	2	133.9	138.0	129.9	5.8	4.3
Theme Along-B	2	2	65.8	67.3	64.2	2.2	3.3
THEME A	16	16	116.6				
Theme B	22	14	176.8	552.4	62.7	138.1	78.1
Theme B -X	1	1	190.4	NA	NA	NA	NA
Theme B-D	31	31	158.2	339.5	66.2	71.5	45.2
Theme B-D-J	2	2	150.6	156.2	144.9	8.0	5.3
Theme B-D-X	6	6	216.9	375.8	85.9	107.1	49.4
Theme B-D-X-J	1	1	188.6	NA	NA	NA	NA
Theme B-F	1	1	118.3	NA	NA	NA	NA
Theme B-F only*	1	1	74.6	NA	NA	NA	NA
Theme B-K	1	1	129.0	NA	NA	NA	NA
Theme B-X	17	17	208.5	449.8	77.2	114.3	54.8
Theme B-X-J	1	1	136.4	NA	NA	NA	NA
THEME B	84	76	158.9				
Theme C-A - short	1	1	84.9	NA	NA	NA	NA
THEME C	1	1	84.9				
Theme D-J	6	6	89.3	148.8	67.8	32.6	36.5
THEME D	6	6	89.3	148.8	67.8	32.6	36.5
Theme F	32	22	145.4	284.2	50.8	84.7	58.2
Theme F2	1	1	63.9	NA	NA	NA	NA
Theme F-A	12	12	141.1	329.3	42.6	84.4	59.8
Theme F-A-B	4	3	153.3	172.1	147.7	77.9	50.8
Theme F-B	3	4	145.7	229.7	84.4	88.5	60.7
Theme F-F2	5	4	174.2	318.8	105.5	115.8	66.5
THEME F	57	46	137.3				

Theme G	11	9	69.3	96.7	33.8	31.5	45.5
Theme G - jfast- K	1	1	184.5	NA	NA	NA	NA
THEME G	12	10	126.9				
Theme J	30	22	91.9	367.6	43.1	72.4	78.8
Theme Jfast	1	1	64.6	NA	NA	NA	NA
Theme J-Jfast	3	2	102.6	220.4	157.6	113.5	110.7
Theme J-high-L	1	1	80.4	NA	NA	NA	NA
Theme J-L	30	30	91.5	171.9	40.4	39.7	43.4
THEME J	65	56	86.2				
Theme K	2	2	61.2	66.7	55.6	7.8	12.8
Theme K-B - short	2	2	65.4	75.9	54.9	14.8	22.7
THEME K	4	4	63.3				
Theme L	10	5	65.3	114.7	34.9	40.3	61.7
Theme L-F - short	1	1	48.7	NA	NA	NA	NA
Theme L-M	8	8	55.0	95.5	37.8	18.3	33.3
Theme L-O	4	3	82.5	136.5	51.2	56.3	68.2
Theme L-O2	1	0	NA	NA	NA	NA	NA
Theme L-O-O2	1	1	73.5	NA	NA	NA	NA
Theme L-P	1	1	199.1	NA	NA	NA	NA
THEME L	26	19	87.4				
Theme M	5	4	67.1	91.4	64.5	34.3	51.1
Theme M-F - short	1	1	38.8				
Theme M-O	5	5	91.0	125.0	60.5	25.9	28.5
THEME M	11	10	65.6				
Theme N	1	1	138.4	NA	NA	NA	NA
THEME N	1	1	138.4				
Theme O	5	4	56.2	80.0	39.1	29.6	52.8
Theme O2	4	4	59.8	98.5	38.1	26.7	44.7
Theme O2-F	1	1	65.3				
Theme O-F	6	5	81.3	119.2	53.9	40.4	49.7
THEME O	16	14	65.6				
Theme P-F	2	2	60.3	61.4	59.2	1.6	2.6
THEME P	2	2	60.3				
Theme W-X	2	2	118.8	162.2	75.4	61.4	51.7
Theme W	2	2	118.8				
Theme X	1	0	NA	NA	NA	NA	NA
Theme X-J	12	11	90.8	129.7	66.3	36.6	40.2
THEME X	13	11	90.8				

Appendix G

Themes

Is there a difference or similarity between the different Theme type durations (ie. Comparing Theme A with Theme B)?

- H_0 : There are no differences between the different theme type's durations
- H_1 : There are differences between the different theme type's durations

*Removed Theme C and N because there is only 1 sample for each theme type.
Bartlett test only works of 2 or more samples.

Bartlett test of homogeneity of variances

Bartlett's K-squared = 89.5217, df = 12, p-value = 6.11e-14

Therefore, reject the null hypothesis.

Kruskal-Wallis rank sum test

Without assuming the data to have normal distribution, test at .05 significance level if the phrase groups have differences between phrase durations.

The null hypothesis is that there is no difference between the phrase durations. To test the hypothesis, we apply the `kruskal.test` function to compare the independent phrase groups. The p-value turns out to be (2.2e-16).

Kruskal-Wallis chi-squared = 102.126, df = 12, p-value < 2.2e-16 >

Hence we reject the null hypothesis, and conclude that there are differences between the Theme type's durations.

Using P value 0.05

[1] 21.02607

Using P value 0.01

[1] 26.21697

Using P value 0.001

[1] 32.90949

Multiple comparisons test between treatments.

A Multiple Comparisons between treatments test was completed to show which groups are different.

- H_0 : Group u and v are similar
- H_1 : Group u and v are not similar

Table G-1. Multiple comparison test after Kruskal-Wallis in R.

p.value: 0.05

Compar.	Obs.dif	Critical.dif	Differ.	F-O	107.8478261	81.96432	TRUE
A-B	44.1694079	73.86169	FALSE	F-P	123.0978261	193.96298	FALSE
A-D	33.2604167	128.54875	FALSE	F-W	16.5978261	193.96298	FALSE
A-F	27.2540761	77.93797	FALSE	F-X	58.2341897	90.12687	FALSE
A-G	82.0937500	108.24774	FALSE	G-J	41.7321429	92.18709	FALSE
A-J	40.3616071	76.12098	FALSE	G-K	3.3750000	158.86425	FALSE
A-K	85.4687500	150.11260	FALSE	G-L	0.3289474	104.90938	FALSE
A-L	81.7648026	91.11489	FALSE	G-M	21.2500000	120.09008	FALSE
A-M	60.8437500	108.24774	FALSE	G-O	1.5000000	111.18181	FALSE
A-O	80.5937500	98.27177	FALSE	G-P	13.7500000	208.00212	FALSE
A-P	95.8437500	201.39719	FALSE	G-W	92.7500000	208.00212	FALSE
A-W	10.6562500	201.39719	FALSE	G-X	51.1136364	117.32902	FALSE
A-X	30.9801136	105.17625	FALSE	J-K	45.1071429	138.97726	FALSE
B-D	77.4298246	113.87192	FALSE	J-L	41.4031955	71.29383	FALSE
B-F	16.9153318	50.16333	FALSE	J-M	20.4821429	92.18709	FALSE
B-G	126.2631579	90.33053	TRUE	J-O	40.2321429	80.23856	FALSE
B-J	84.5310150	47.29098	TRUE	J-P	55.4821429	193.24004	FALSE
B-K	129.6381579	137.75277	FALSE	J-W	51.0178571	193.24004	FALSE
B-L	125.9342105	68.87639	TRUE	J-X	9.3814935	88.56032	FALSE
B-M	105.0131579	90.33053	TRUE	K-L	3.7039474	147.72339	FALSE
B-O	124.7631579	78.09848	TRUE	K-M	24.6250000	158.86425	FALSE
B-P	140.0131579	192.36128	FALSE	K-O	4.8750000	152.24197	FALSE
B-W	33.5131579	192.36128	FALSE	K-P	10.3750000	232.55344	FALSE
B-X	75.1495215	86.62607	FALSE	K-W	96.1250000	232.55344	FALSE
D-F	60.5144928	116.55724	FALSE	K-X	54.4886364	156.78750	FALSE
D-G	48.8333333	138.66808	FALSE	L-M	20.9210526	104.90938	FALSE
D-J	7.1011905	115.35020	FALSE	L-O	1.1710526	94.58196	FALSE
D-K	52.2083333	173.33510	FALSE	L-P	14.0789474	199.62273	FALSE
D-L	48.5043860	125.75050	FALSE	L-W	92.4210526	199.62273	FALSE
D-M	27.5833333	138.66808	FALSE	L-X	50.7846890	101.73716	FALSE
D-O	47.3333333	131.02902	FALSE	M-O	19.7500000	111.18181	FALSE
D-P	62.5833333	219.25349	FALSE	M-P	35.0000000	208.00212	FALSE
D-W	43.9166667	219.25349	FALSE	M-W	71.5000000	208.00212	FALSE
D-X	2.2803030	136.28393	FALSE	M-X	29.8636364	117.32902	FALSE
F-G	109.3478261	93.69302	TRUE	O-P	15.2500000	202.98929	FALSE
F-J	67.6156832	53.43420	TRUE	O-W	91.2500000	202.98929	FALSE
F-K	112.7228261	139.98072	FALSE	O-X	49.6136364	108.19365	FALSE
F-L	109.0188787	73.23069	TRUE	P-W	106.5000000	268.52959	FALSE
F-M	88.0978261	93.69302	FALSE	P-X	64.8636364	206.42033	FALSE
				W-X	41.6363636	206.42033	FALSE