Te Reo Hihi: Vocal individuality as a tool for conservation and monitoring of the rare Hihi

MSc Thesis
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Abstract

Effective, non-invasive methods in conservation biology are increasingly important for monitoring populations of endangered animal species. Bioacoustics, particularly individual acoustic monitoring (IAM), promises an effective strategy to determine population size and individual identity, yet its feasibility in conservation monitoring remains unexplored. In this study, I investigated the vocal individuality of male hihi (*Notiomystis cincta*) in Tarapuruhi Bushy Park, an ecosanctuary in New Zealand, to assess the potential of IAM for conservation monitoring. My aim was to determine (1) individual distinctiveness in the male song to assess if the song could be a (male) population monitoring tool, and along this line (2) similarities in neighbour song, which would help understanding the relations among neighbours, next to being important to separate neighbour recordings for monitoring. I recorded and analysed the song repertoires of nine males, identifying between 7 and 23 unique song types per individual. The accumulation of song types was strongly influenced by recording effort and time. Furthermore, no difference was found in repertoire similarity between neighbours and non-neighbours. Using two unique song types, spectrogram cross-correlation successfully distinguished individuals singing the same song type based on their vocal signatures, demonstrating the method's potential for individual identification. These findings highlight the potential of vocal individuality for monitoring male hihi while underlining its inherent bias towards the males in a population, thus not capturing the full diversity of a population. Moreover, the time-intensive nature of recording full repertoires may limit its application for large-scale monitoring. Future research should examine the potential for identifying females from vocalisations and assess the effectiveness of automated omnidirectional recorders along with automated computer-based song analyses as a more scalable solution for conservation monitoring.

Keywords: acoustic monitoring, conservation, hihi, vocal individuality

1. Introduction

The growing human population has led to a severe decline in biodiversity, with species extinction rates now estimated to be 1000 times higher than the background rate of extinction (Pimm et al., 2014). Human actions such as habitat loss and degradation, overexploitation of resources, introduction of invasive species, pollution and climate change, have resulted in biodiversity loss becoming an urgent environmental crisis (Hogue & Breon, 2022). Loss of biodiversity threatens ecosystem stability, reducing ecological services that humans depend on, such as food production, clean water supply, carbon sequestration and climate regulation. For example, the decline of pollinator species (16% of vertebrate pollinators and 40% of invertebrate pollinators at risk of extinction) has already begun to impact global agriculture (Brunet & Fragoso, 2024). These trends highlight the need for conservation efforts to protect biodiversity and maintain the ecosystem services which are crucial for human well-being (Cardinale et al., 2012).

Aotearoa New Zealand's isolation from the rest of the world has led to the development of a rich and unique biodiversity, with many species found nowhere else on Earth. However, this distinctiveness also makes New Zealand vulnerable to invasive species and habitat degradation, and since the arrival of European colonisers many native species have experienced severe declines in numbers, with some being driven to extinction (King 2019). In response, New Zealand has implemented ambitious conservation initiatives, including the creation of predator-free sanctuaries, pest eradication programs, restoration of degraded habitats, community-led conservation projects, and the ambitious goal of becoming predator-free by 2050. One key conservation strategy employed in New Zealand is the translocation of native species, including their reintroduction into areas where they were once abundant and their establishment in predator-free sanctuaries. One example is the Tieke (North Island saddleback: *Philesturnus rufusater*) , once confined to a single island population, has now been translocated to 18 mainland populations. Other successfully translocated bird species include the toutouwai (North Island Robin: *Petroica longipes*and) and North Island kōkako (*Callaeas wilsoni*) (Parker et al., 2023). However, the success of translocations is limited, as they are complex multifaceted efforts, involving ecological, logistical, and environmental challenges. Many of New Zealand's native species are sensitive to environmental conditions, which can affect the outcomes of these efforts (Parker et al., 2023). Despite these challenges, translocations remain a critical tool in New Zealand's conservation strategy, offering a tool for the restoration and protection of its unique biodiversity.

One such translocated species is the hihi (Stichbird; *Notiomystis cincta;*), a small forest-dwelling passerine. The hihi belongs to the family Notiomystidae, of which it's also the only known member. The species is classified as nationally vulnerable under the New Zealand Threat Classification System (Robertson et al., 2021) and vulnerable by the IUCN Red List (IUCN 2024). By the 1880's, the only remaining hihi population was confined to Te Hauturu-o-Toi, or Little Barrier Island, with the species having become extinct on mainland New Zealand (Metcalf et al., 2019). Habitat loss, introduction of mammalian predators and new avian diseases are assumed to be the most likely causes of extinction (Taylor, Castro & Griffiths, 2005; Ewen et al., 2018). The disappearance of hihi is concerning since they require diverse and intact forest ecosystems and thus provide a litmus test for the state of the forests of New Zealand's North Island. Furthermore, hihi are nectar-eating and thus important pollinators. Loss of hihi has led to loss of ecosystem services related to pollination, causing reduced seed production and plant density (Ewen et al., 2018).

Given the importance of conserving hihi, since 1980 hihi populations have been actively managed, and reintroductions have been used to increase the species' range and population size. Reintroduced populations have had mixed successes with only 50% of translocation sites able to maintain a population (Ewen et al., 2018). Successful translocations have resulted in seven reintroduced populations across the North Island (Figure 1; Hihi conservation trust, 2024). Despite these successes, hihi remain vulnerable to predation and disease, and all the reintroduced populations are intensively managed (Richardson et al., 2016). Management includes biosecurity control (by maintaining predator-proof fences and active trapping), supplementary feeding of sugar water and in some cases provision of artificial nest boxes (Panfylova et al., 2016). Monitoring these populations can present multiple challenges due to the ecology and behaviour of hihi. Hihi are forest-dwelling birds and typically inhabit dense forests, making them difficult to spot visually. Their small size and inconspicuous colours in females further complicate visual detection (Metcalf et al., 2019). However, hihi are a highly vocal species with both males and females producing 'stitchcalls', although only the males sing (Higgins et al., 2001). Male songs are thought to be mainly associated with territorial behaviours, particularly during the breeding season when vocalisations are vital for mate attraction and territory defence (Ranjard et al., 2017). The song of hihi males consists of a high-pitched whistle of two to three beats (Higgins et al., 2001). A male can produce several song variants in one song bout which are taken from his song repertoire (Ranjard et al., 2015).

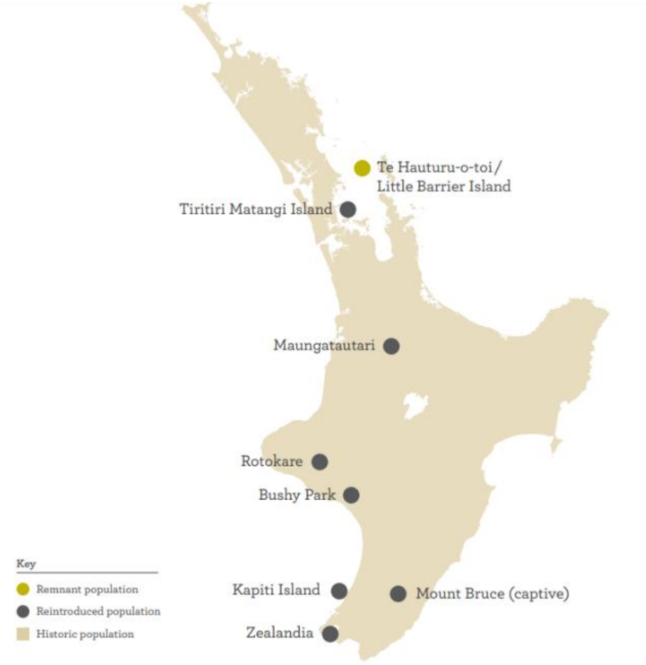

Figure 1: Locations of reintroduced populations of hihi across the North Island ***©Hihi Recovery Group.***

The active monitoring of hihi populations is time-intensive and labour-demanding, particularly in dense forest habitats where visual surveys are challenging. Given the vocality of hihi, passive acoustic monitoring (PAM) could be a promising and efficient technique for monitoring these populations (Vu & Doherty, 2021). Passive acoustic monitoring is a method that records and analyses animal vocalisations to detect the presence, distribution and behaviour of animals. It has been applied to monitor endangered vocal species across several taxa. For instance, Zwart et al. (2014) successfully used PAM to detect the presence of European nightjars in the United Kingdom and found PAM to be more accurate in detecting nightjars compared to human surveys. Similarly, PAM has been used to study the vocal behaviour, distribution and population density of gibbons in Vietnam (Vu & Tran, 2019) and to estimate African elephant abundance in large and remote areas (Thompson et al., 2009). The growing use of PAM in conservation provides a non-invasive way to monitor endangered species, while minimizing human disturbance (Celis-Murillo et al., 2012). Within PAM, Individual acoustic monitoring (IAM), focuses specifically on identifying and tracking individual animals based on their unique vocal signatures (Onate-Casado et al., 2023). Individually distinctive vocal features have been shown in a variety of animal species, and are thought to be present in all vocally active species (Petruskova et al., 2016; Lewis et al., 2020). This variation is affected by morphology, such as body size and beak shape. Vocal repertoire and the size of the repertoire can also vary between individuals of the same species (Lewis et al., 2020). A requirement for individual recognition is that there should be low within-individual variation and high between-individual variation (Terry et al., 2005).

Despite its advantages, studies on hihi using bioacoustics are relatively limited. The few existing studies focus on vocalisations during copulation (Castro et al., 1996; Low 2005b), territory defence and mate guarding (Low 2005a) and geographic variation in song variants (Ranjard et al., 2015; Ranjard et al., 2017). One study used acoustics to study the post-translocation behaviour of hihi and found that acoustics is an effective method for monitoring post-release dispersal (Metcalf et al., 2019). However, broader applications of bioacoustics, such as its use for established population monitoring or studying vocal individuality, remain unexplored. Expanding the scope of bioacoustics studies could provide valuable tools for managing hihi populations more effectively and addressing critical knowledge gaps in their conservation. No published studies exist exploring the vocal individuality in the hihi, though studies on other bird species have shown that there are individual differences in vocalisations (Terry et al., 2005). Individually distinctive vocalisations are used by animals to discriminate among conspecifics and can be used for monitoring and surveying an established population (Blumstein et al. 2011). By identifying hihi individuals through their vocalisation, conservationists can reduce reliance on visual identification methods like reading colour bands, which are challenging in dense forests. According to one paper by Castro et al in 1996, hihi males are identifiable by territorial call, but research confirming this remains non-existent.

To be able to use vocal individuality for conservation we need to learn more about the structure and variability of hihi song. Measuring the song repertoire size and the repertoire similarity allows us to determine the degree of song sharing between individuals. This is especially important to investigate for birds occupying neighbouring territories since in many songbirds it is known that territorial neighbours share parts of their song repertoire (Price & Yuan 2011; Beecher & Brenowitz, 2005). If neighbours share more of their song repertoire than with non-neighbours, this will make individual identification by song more complex. Furthermore, if some song types are shared across individuals, identifying individuals may still be possible based on slight, subtle differences. This is generally investigated using spectrogram cross-correlation which involves taking each song of each male and calculating the percentage of overlap with each song of all other males; songs that are very similar result in a high spectrogram cross-correlation score (Foote, Palazzi & Mennill, 2013).

This study aims to determine the application of vocal individuality in male song for monitoring an established hihi population in Tarapuruhi Bushy Park, an ecosanctuary in New Zealand. The aim is by characterizing individual song parameters and those parameters which are shared in a population and specifically among neighbours, to deepen the understanding of hihi song and contribute to the development of non-invasive monitoring techniques for hihi conservation efforts. Specifically, by determining the size of the song repertoire of hihi, the extent of song sharing and how this might be influenced by the repertoire of neighbouring hihi. Along this line, the study also explores whether subtle variations in distinct song types can be used for individual hihi identification.

2. Methods

2.1 *Study site: Tarapuruhi Bushy Park*

I conducted the research on the hihi population at Tarapuruhi Bushy Park, New Zealand, from October 2024 to mid-January 2025. This period coincides with the hihi breeding season during New Zealand's Spring and Summer months. Tarapuruhi Bushy Park is an 89-hectare forest sanctuary near Whanganui on the North Island of New Zealand. The forest is a North Island temperate lowland forest consisting of broadleaf podocarp with mainly tawa (*Beilschmiedia tawa)*, pukatea (*Laurelia nocaezelandiae*), rimu (*Dacrydium cupressinum*) and northern rātā trees (*Metrosideros robusta*). The forest is relatively unmodified, no logging or burning has ever taken place in the main forest. In 2005 the forest was fenced with a 4.8km Xcluder pest fence to keep out introduced mammalian predators (except for mice) and livestock (Tarapuruhi Bushy Park – Tarapuruhi Bushy Park Forest Sanctuary & Historic Homestead) (Figure 2).

2.2 *Study animal: Hihi (Notiomystis cincta)*

In 2013, 44 juvenile hihi were reintroduced to Tarapuruhi Bushy Park from a population on Tiritiri Matangi Island (Panfylova et al., 2016). Currently, it's estimated that there are around 50 hihi residing in Tarapuruhi Bushy Park though exact numbers are unknown. During a pre-breeding season survey conducted by Hihi conservation officer Erin Patterson in September 2024, a total of 29 hihi were identified, of which 25 were males and four females. The hihi in Tarapuruhi Bushy Park are supplementary fed with sugar water at five sugar water feeders around the park. Most of the hihi are colour-banded and RFID-banded. The RFID bands are registered when the birds enter the sugar water feeder, and this data is collected weekly. There are also 48 artificial next boxes which the hihi have used in the past (Tarapuruhi Bushy Park – Tarapuruhi Bushy Park Forest Sanctuary & Historic Homestead). During the breeding season, these nest boxes are monitored weekly by volunteers to check for nesting activity and chick survival. Hihi are sexually dimorphic, with males having black, white and yellow plumages, whereas females are more subtly coloured with brown and grey plumages (Higgins et al., 2001).

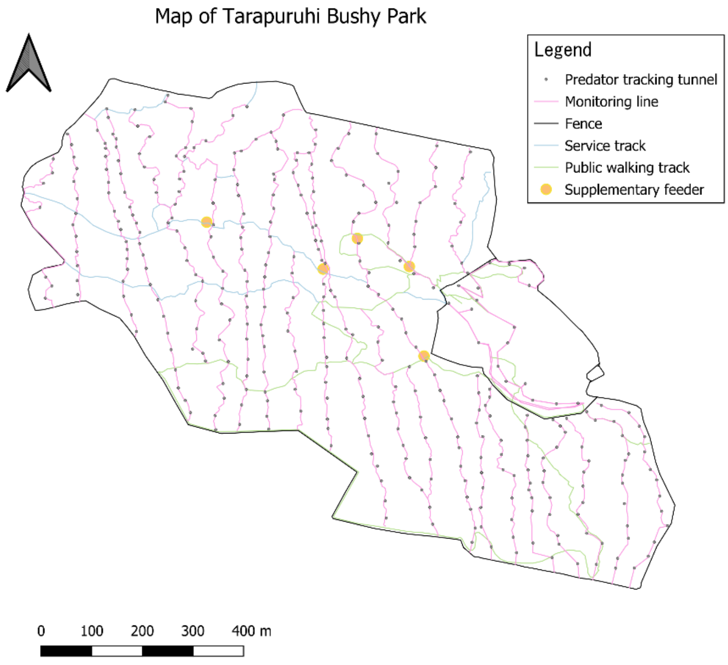

Figure 2: Map of the study site Tarapuruhi Bushy Park.

2.3 *Acoustic survey*

To determine the recurring locations of the hihi in the park I conducted an acoustic survey from October 16th to November 1st 2024 using the omnidirectional microphone of the Tascam DR-100MK3 PCM recorder. During this audio survey, I walked the existing monitoring lines and made recordings every 100 meters at the rodent tracking tunnels to determine the presence of hihi. From this survey, a list of locations where hihi were sighted or heard was conducted and this was used for the individual recordings later in the study. Most of these locations coincided with the presence of a nestbox or feeder (Figure 3).

2.4 Individual acoustic recordings

Recordings were made of spontaneously singing males at sites determined from the acoustic survey from 23rd October 2024 to 12th January 2025. Recordings were made on days where weather allowed (no recordings on days with rain and high wind because of safety reasons and high background noise) using the directional microphone of the Tascam DR100MK3 PCM. I made recordings at the active nestboxes, feeders and additional locations across the park that were identified during the acoustic survey (Figure 3). To capture individual variation in vocalisations across the breeding season as many recordings as possible were made to determine the repertoire of each hihi. A recording started only after a hihi was heard singing and was identified by its colour bands. I visited each known location, waited 20 minutes for the hihi to vocalise and come close enough to be able to read the colour bands. I recorded the hihi until it flew away from my location (following a hihi was not possible due to the dense forest vegetation). After the hihi flew away I waited another 20 minutes for it to return, if so, I would record until it flew away again. If nothing was heard after 20 minutes I moved on to another location. I aimed to visit all locations during a morning session, if a hihi was not sighted during the morning session an attempt to locate and record it was made in an afternoon session of the same day.

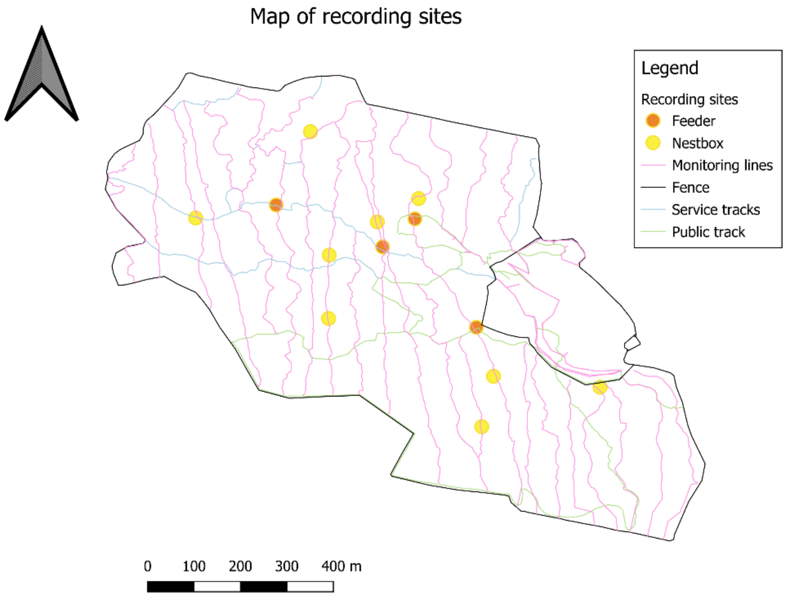

Figure 3: Map of recording sites as identified from the acoustic survey, dots represent recording sites, yellow dots represent nestboxes and orange dots represent feeders.

The individual acoustic recordings were embedded in intensive monitoring of the hihi breeding season. During this monitoring, active nests were first checked daily and later in the season fortnightly for chick development and mortality. These checks included waiting at least 15 minutes to ensure a parent was not on the nest, opening the nest box and noting the number of eggs and chicks. Monitoring also included updating a database with nestbox numbers, colour combos of parents, number of eggs and chicks, projected hatch, banding and fledge dates and nest box cleaning dates. Furthermore, banding dates were arranged with hihi banders and equipment checking was done. Throughout the 2024-2025 hihi breeding season, there were 12 breeding attempts of which five nests produced fledglings, adding up to a total of 16 fledglings.

2.4 *Song spectrogram database*

A total of 13 males were recorded but five of them were excluded from the analysis since they had less than three recording dates (I chose at least three days to account for any variation in songs between days). For the nine remaining males, a total of 836 songs were extracted from 1461 minutes of recordings (24 hours and 21 minutes). The number of songs recorded per male ranged from 24 to 134, with individual recording durations ranging from 45 to 249 minutes. All recordings were organized per individual bird and visualized as a spectrogram using Avisoft SASlab Pro (FFT 512 and Hamming window). Hihi song were manually detected and labelled based on visual inspections of the spectrograms. I recognized hihi song by their general properties of 2-3 notes/elements and a frequency range between 5 and 20kHZ (Higgins et al., 2001; Ranjard et al., 2017). Any song recordings with too much background noise or overlapping noise of other birds (e.g. toutouwai (*Petroica longipes*) and tieke (*Philesturnus rufusate*)) were excluded from the analysis. Additionally, song recordings where the bird was too far away (resulting in low quality or uncertainty about the identity of the individual) were also excluded. Each song spectrogram was extracted and saved to an Excel database by individual and numbered sequentially by occurrence and date. From this database, each song was categorized into a unique song type and assigned a number from 1 to 48 corresponding to the 48 song types. I assigned songs to the same type if they did not differ in more than two basic song components and their syntactical arrangement (Grießmann and Naguib 2002). The unique set of song types per bird formed his song repertoire (see Figure 4 for the repertoire of one male; the song repertoire of each male can be found in Appendix 1). The song repertoire is the full set of songs that a single individual produces and the song repertoire size is the total number of different song types an individual produces (Lewis et al., 2020). From the database of song spectrograms, I created a dataset with Nickname, recording date, time of recording, song_ID and song type for each male to be used for further data analysis.

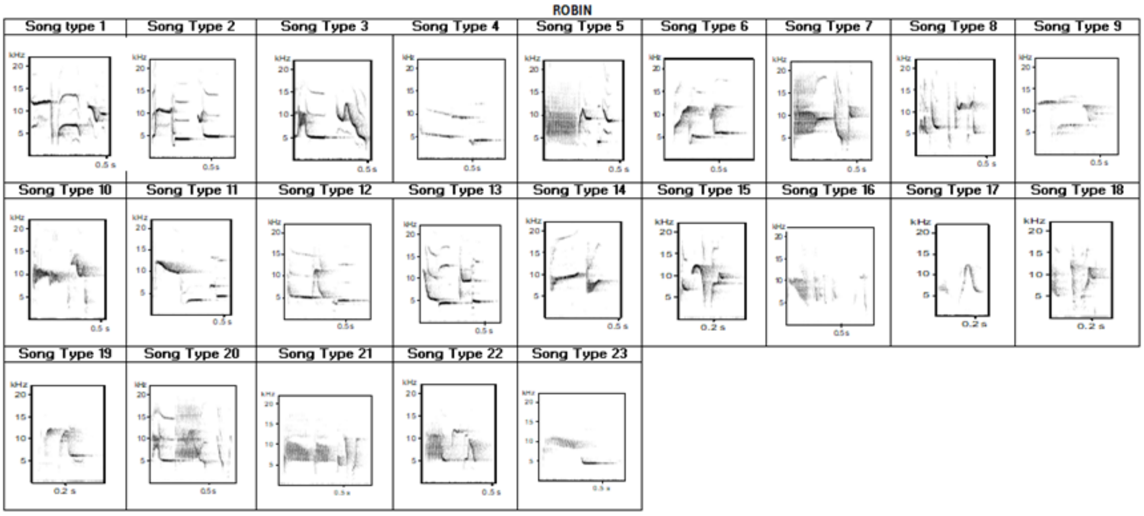

Figure 4: Full song repertoire of hihi 'Robin'.

2.4 *Repertoire size and sharing*

All data analysis was done in R studio version 4.3.1 (R-core-Team 2024). The song repertoire dataset was used to create cumulative curves, visualizing how the repertoire size increased with recording time and number of songs recorded. Two separate models were fitted. Because of a strong correlation between recording time and the number of songs recorded (r = 0.82), two separate linear models were fitted to assess their individual effects on the song repertoire. One model included recording time, individual nickname, and their interaction, while the other model incorporated the number of songs recorded, individual nickname, and their interaction.

I visualized neighbouring territories using QGIS version 3.34.11 (QGIS development team 2025). I collected the GPS coordinates of the nine males during the acoustic survey and individual recording sessions and assembled these in clusters assigned to each male. From this the average GPS location was calculated and used to create tessellated polygons (Wilkin et al., 2007) (Figure 5). Each pair of males was categorized as 'neighbours' or 'non-neighbours' based on whether their tessellated territories shared a border. The tessellation resulted in a total of 36 pairs, of which 16 pairs between neighbours and 20 pairs between non-neighbours.

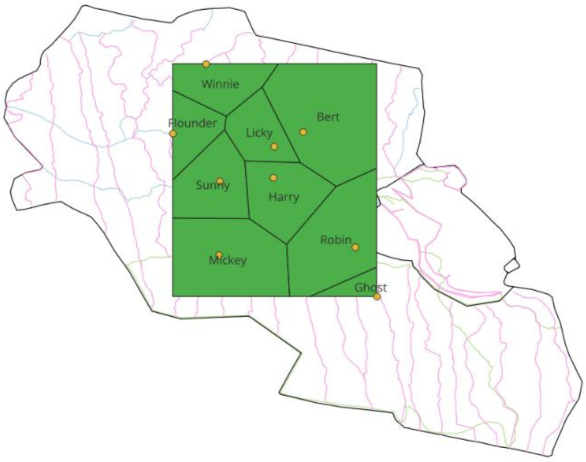

Figure 5: Tessellated territories of the nine males.

To determine the degree of repertoire sharing between each pair of males I calculated the index of repertoire sharing using the following formula: RS = Z/((X + Y) – Z), with X and Y being the number of song types of birds x and y, and Z being the number of shared song types (Naguib & Grießmann 2002; Price & Yuan 2011). The RS index can range from 0 (no song types shared) to 1 (all song types shared) and accounts for the fact that different males can have different numbers of identified song types (Price & Yuan 2011). I compared the repertoire sharing index between neighbouring and non-neighbouring pairs first using a Mann-Whitney U test. Due to ties in the data, I also performed permutation tests.

2.5 Song type spectrogram cross-correlation

To investigate if song types could be used for individual identification, I used spectrogram cross-correlation. This method has previously been applied successfully in other species. For example, one study by Foote, Palazzi and Mennill (2012) found that songs of the same male Eastern Phoebes from different recording sessions were more similar than songs of different males (Foote, Palazzi & Mennill 2012). They found this for two song types and used multiple methods among which spectrogram cross-correlation and found significantly more variability among than within males for both song types. Similarly, Xia et al. (2011), showed that spectrogram-cross correlation could be used to reliably identify individual Asian Stubtails and found it to be a more suitable method compared with discriminant function analysis and artificial neural networks.

To test if individual males can be identified by their unique song types, for two of the most common of the 48 song types, I conducted a spectrogram cross-correlation using the correlator from Avisoft SASlab Pro. I randomly selected two recordings of different recording sessions of the song type for each male with that song type in his repertoire and put all of these in a correlation matrix. Avisoft correlation calculated the correlation values between each recording. I then copied these values into a matrix for R. I calculated the average cross-correlation scores between and within the individuals. I then tested if there was a difference in the average cross-correlation scores within individuals compared to between individuals using a Wilcoxon rank-sum test. For song type 3 eight out of nine males had this song type, but two of the males only had one recording of this unique song type (Figure 9). Because of this I excluded these two males from the analysis and continued the analysis with six of the males. For song type 22, eight out of nine males had this song type, but one individual only had one recording and was excluded from the analysis. I then continued with seven males in this analysis (Figure 11).

3. Results

3.1 *Song repertoire size*

A total of 48 unique song types were identified and individual song repertoire sizes ranged from 7 to 23 song types, with an average repertoire size of 15 (Table 1).

Table 1: Total recording time, total number of songs and number of song types identified per male hihi.

Nickname	Colour band combination	Total minutes recorded (m)	Number of songs recorded	Number of song types identified (Repertoire size)
Robin	DB-DG/M	228.67	108	23
Winnie	LG-DB/M	44.5	24	12
Flounder	Y-DB/M	156.18	65	12
Harry	LB-W/M	190.63	120	19
Sunny	W-DG/M	114.48	127	7
Ghost	W-W/M	185.02	78	19
Mickey	Y-O/M	62.72	51	14
Bert	Y-DG/M	248.65	129	20
Licky	W-DB/M	229.92	134	19

Repertoire size increased significantly with both recording time and the number of songs recorded, although the rate of accumulation varied among individuals. In models assessing the accumulation of song types, cumulative repertoire size was strongly influenced by recording time (F (1,818) = 14768.68, *P* < 0.001) and number of recorded songs (F(1,818) = 5148.28, *P* < 0.001), as well as by individual identity (recording time model: F(8,818) = 196.23, *P* < 0.001; song number model: F(8,818) = 395.08, *P* < 0.001) and their interactions (F(8,818) = 14.90 and F(8.818) = 181.58, respectively, both *P* < 0.001). While the cumulative repertoire curves for all individuals approached an asymtote, specifically when considering the recording time (Figure 6b), for the majority of individuals, the full repertoire was likely not captured completely (Figure 6ab).

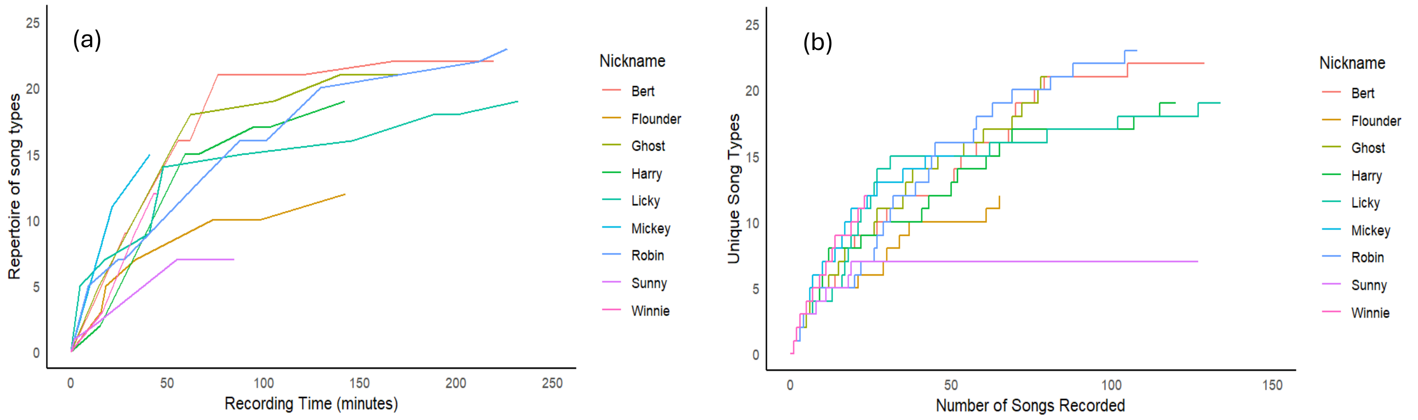

Figure 6: Cumulative curves showing the number of identified song types as a function of recording time in minutes (a) and number of songs recorded (b) for nine hihi males.

3.2 Song repertoire sharing

Across the nine males, none of the 48 identified song types were shared by all individuals. The most common song types - types 3 and 22 (Figure 9 and Figure 11) - were present in eight out of nine individuals. Song types 4, 11 and 13 occurred in seven out of nine individuals. Fourteen song types were unique to a single male (Figure 7).

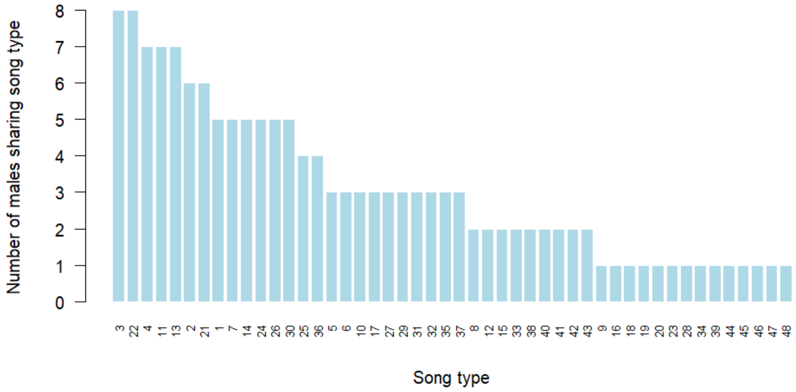

Figure 7: Number of males that sing each song type.

Pair-wise comparisons of the repertoires of the males revealed that repertoire-sharing scores ranged from 0 to 0.53 (mean ± SE = 0.24 ± 0.14.) There was no significant difference in the repertoire similarity scores between neighbours and non-neighbours (Mann Whitney U test: W = 195.5, P = 0.27, permutation test: P = 0.19) of neighbours vs non-neighbours (Figure 8). The mean RS scores were 0.30 ± 0.09 for neighbours and 0.25 ± 0.13 for non-neighbours. This suggests that neighbouring males do not share more of their song repertoire compared to non-neighbours.

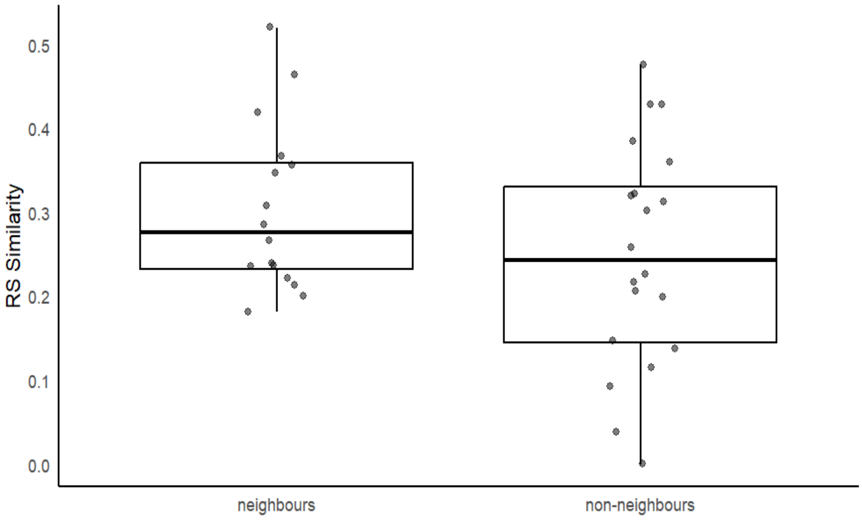

Figure 8: Boxplots of RS similarity for pairs of neighbours (N = 16) and non-neighbours (N=20).

3.3 Song type differences between individuals

Spectrogram cross-correlation analysis revealed that within-individual cross-correlation values for song type 3 were significantly higher than between-individual values (Wilcoxon test: W = 296, N = 56, P < 0.001), with a mean within-individual coefficient of 0.71 and a mean between-individual coefficient of 0.33 (Figure 10). A smaller but still significant difference was also observed for song type 22 (Wilcoxon test: W = 382.5, N= 79, P = 0.025), with mean within- and between-individual coefficients of 0.52 and 0.39, respectively (Figure 12). These results indicate that both song type 3 and 22 are individually distinctive.

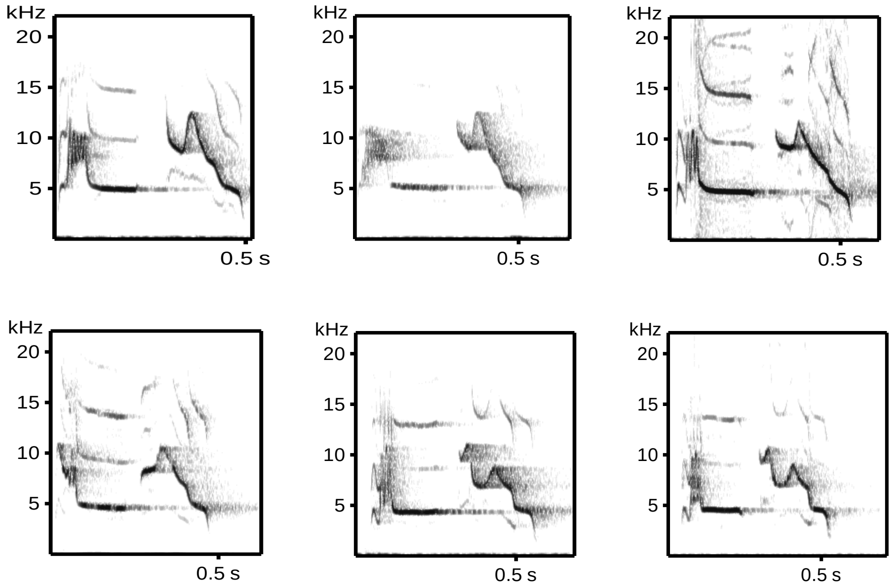

Figure 9: Song type 3 sung by six different males.

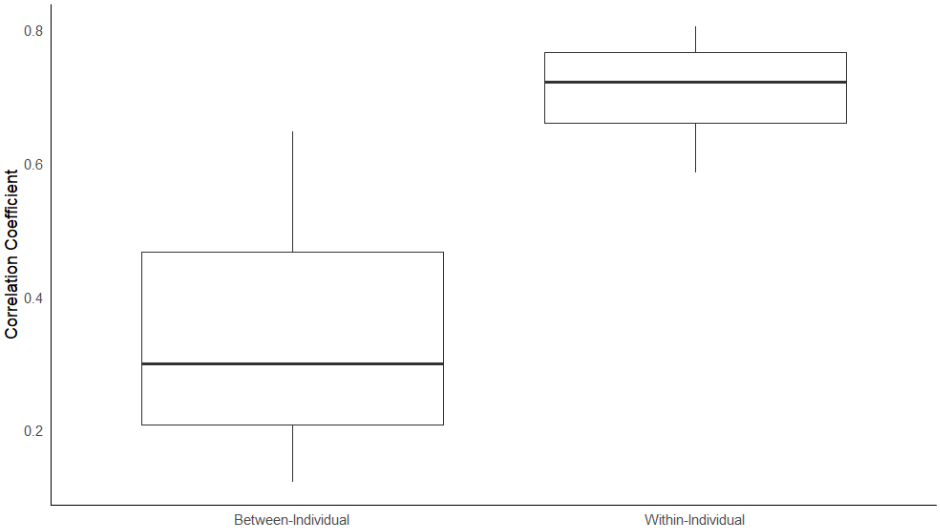

Figure 10: Boxplots of the correlation coefficient for all pairs between individuals (N = 50) and within individuals (N = 6) for song type 3.

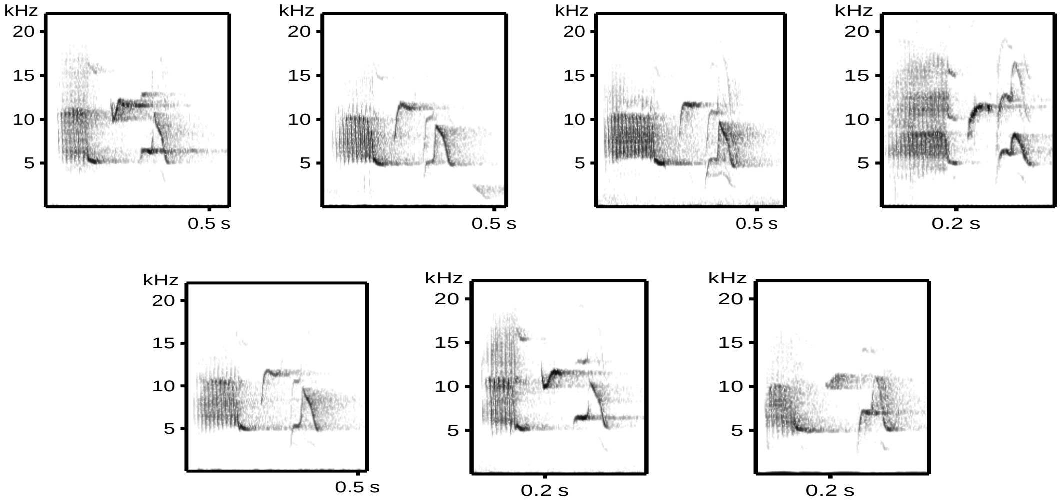

Figure 11: Song type 22 sung by seven different males.

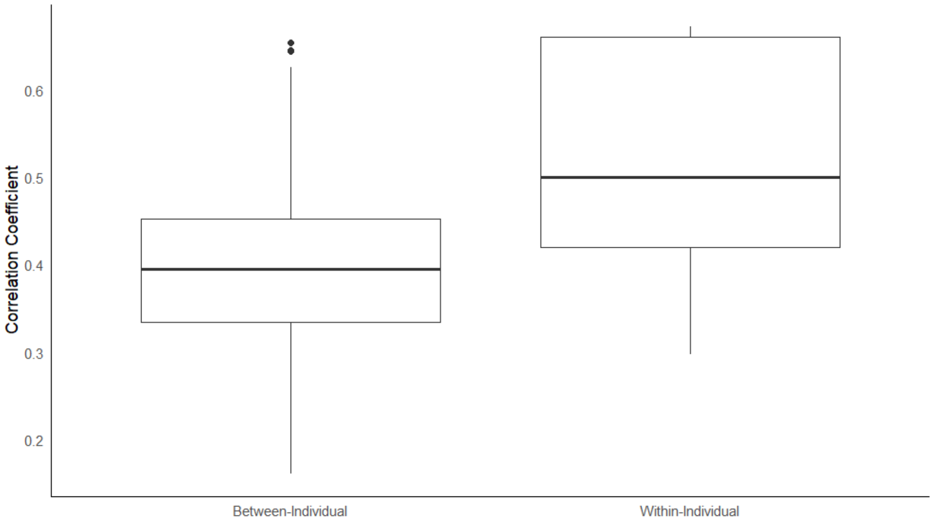

Figure 12: Boxplots of the correlation coefficient for all pairs between individuals (N = 77) and within individuals (N= 7) for song type 22.

4. Discussion

In this study, I investigated the vocal behaviour of male hihi in Tarapuruhi Bushy Park, focussing on song repertoire size, sharing, and individual distinctiveness. The accumulation of song types was strongly influenced by both recording time and the number of songs recorded. For the majority of males, the cumulative curves approached a plateau, yet further recordings would likely reveal more songs per male. There was no significant difference in repertoire similarity between neighbouring and non-neighbouring males, indicating that proximity does not appear to influence song sharing. Additionally, the analysis of shared song types revealed that these song types still had individually distinctive features, with higher cross-correlation values within individuals compared to between individuals. These findings contribute to the understanding of vocal individuality in hihi, with implications for monitoring population structure and social dynamics.

I found a total of 48 different song types and an average song repertoire size of 15. These were both larger than in a previous study on Tiritiri Matangi, where they found 16 different song types and an average repertoire size of 9 song types (Ranjard et al., 2015). The differences in song repertoire size between the two populations could be explained by differences in habitat composition (Kroodsma, 2004). The forest of Tarapuruhi Bushy Park is older and more ecologically complex compared to that of Tiritiri Matangi. It has been shown that more complex habitats can encourage greater vocal diversity as birds adapt their songs to optimise communication in varying environments (Boncoraglio & Saino, 2006). Additionally, in populations with higher densities or more complex social systems, selection may favour larger repertoires because males engage in more frequent or varied social interactions, including mate attraction and male–male competition (Beecher & Brenowitz, 2005). Tarapuruhi Bushy Park may have higher hihi density or more intense territorial interactions than Tiritiri Matangi, favouring vocal diversity. Methodological differences may also contribute to the different results. I manually assigned song types, while Ranjard et al. (2015) used automated classification. Although manual classification can reliably distinguish vocalisations (Janik et al., 2006), it may introduce observer bias. Future studies should aim to reduce subjectivity by using multiple observers or combining manual and automated methods (Terry et al., 2005).

I found that neighbouring males did not share significantly more song types than non-neighbours, with a mean RS index of 0.30 for neighbours and 0.25 for non-neighbours. While these RS values are higher than those reported in some previous studies—such as in tropical mockingbirds (0.10 for neighbours and 0.036 for non-neighbours) (Price & Yuan, 2011)—they are comparable to findings in thrush nightingales (0.38 for neighbours and 0.27 for non-neighbours) (Grießmann & Naguib, 2002), where a significant difference between groups was indeed observed. The absence of a significant difference in song sharing between neighbours and non-neighbours might be explained by the fact that males in Tarapuruhi Bushy Park are not completely isolated within their territories due to supplementary feeding. Five sugar water feeders are supplied across the park, each typically located in one male's territory. While these males defend the feeders, they are not the sole users. Feeders act as hubs where males can encounter and interact with each other, likely more frequently than they would in an unmonitored setting without shared feeders (Roper & Brunton, 2023). In this way, feeders may present opportunities for song learning, where males may not only interact with their immediate neighbours, but also with males from across the park, which could explain why there is no clear evidence of greater song sharing among neighbours compared to non-neighbours. This relates to findings in the white-crowned sparrow, where song sharing did not correlate with proximity to neighbours and territory tenure. Instead, they argued that other factors, such as social interactions, may be more influential than just proximity to other males (Nelson & Poesel, 2013). Lastly, there is no immigration into the Tarapuruhi Bushy Park population (except for any future top-ups), so there is little opportunity for new song types to be introduced into the population. As a result, the song repertoire composition remains stable, and the potential for increased song sharing is reduced (Recalde et al., 2023b).

I found that individual male hihi can be identified by subtle differences in at least two of their song types. Spectrogram cross-correlation analysis revealed that within-individual similarity was significantly higher than between-individual similarity for both song types 3 and 22, indicating individual distinctiveness. The correlation coefficients observed (e.g., 0.71 within vs. 0.33 between for song type 3) are comparable to those reported in Eastern Phoebes (Foote, Palazzi & Mennill, 2012), suggesting a similar potential for individual vocal recognition. This variation in song type structure may enable hihi to recognize familiar individuals, such as neighbours and mates. The ability to distinguish between individuals likely plays an important role in both mate selection and territorial defence (Kroodsma & Byers, 1991). For example, males could use vocal cues to distinguish between neighbours and strangers, potentially developing "dear enemy" relationships, in which familiar rivals are challenged less aggressively than strangers (Ehnes & Foote, 2014; Petrusková et al., 2016). These relationships may promote territorial stability and reduce the energetic costs of frequent aggression. Similarly, females may use individual recognition to assess the quality of potential mates and to eavesdrop on vocal interactions between their mates and neighbouring males when making decisions about extrapair copulations (Ehnes & Foote, 2014).

Challenges of using vocal individuality

This study has successfully demonstrated that individual male hihi can be identified by their song, which is a significant step forward in using vocal individuality as a monitoring tool. However, it is important to note that this method is inherently biased towards males due to their higher vocal activity. Females of avian species are generally quiet, making it difficult to monitor female birds using vocal individuality (Terry et al., 2005). Female hihi are no different and do not sing. They are known, however, to produce stitchcalls, though no studies exist on the differences between male and female stitchcalls and the potential for using female stitchcalls to identify individuals. Stitchcalls by females are generally made when entering or leaving the nest and could be recorded for nesting females. Kipper et al. (2014) found that in nightingales, calls from males and females differed in several acoustic parameters and Węgrzyn et al. (2021b) found that woodpecker contact calls were both individually distinctive and sexually dimorphic. These findings suggest that stitchcalls may contain sufficient variation for identifying individual female hihi, though this requires extensive acoustic analyses. Playback experiments may be used to identify individual females but must be designed carefully to avoid any disturbance during the nesting period. Another prerequisite for using vocal individuality as a monitoring tool is temporal stability. The repertoire size and composition of males will need to be consistent across multiple breeding seasons in order to be reliable for monitoring (Petruskova et al., 2016). The current study was limited to a single breeding season and was the first instance of collecting song data for this population. Future research should thus include data collection over multiple years, to evaluate the consistency of individual song.

Conservation applications

The aim of this study was to investigate the potential of using bioacoustics and vocal individuality as a tool for hihi conservation, while also considering time and labour constraints. To study the song repertoire of hihi effectively, it is crucial to determine whether the full repertoire has been recorded. While I was able to capture the full repertoire for a few individuals, for others—including those with over 100 recorded songs—it remains uncertain whether their full repertoire was obtained. The only other study on hihi song variants by Ranjard et al. (2015), reported a total of 1879 songs from 22 individual males, but did not mention the amount of songs recorded per male. There thus remains no consensus on the repertoire size of hihi males and how many song recordings are needed to capture the full repertoire.

One potential solution is the use of automated omnidirectional recorders, which have been found to be valuable for individual recognition and following individuals across multiple years (Ehnes & Foote, 2014). While directional microphones, as used in this study, produce high-quality recordings, individuals need to be manually recorded, which can lead to high effort per recording. Ehnes & Foote, 2014 found that songs of individual Ovenbirds could be discriminated from automated recordings, even low-quality recordings could be used to reliably discriminate individuals using spectrogram cross-correlation. I also deployed automated omnidirectional recorders as part of this study, but due to time constraints, those recordings were not analysed. Future studies should compare these recordings with the directional microphone data to evaluate their usefulness for identifying individual hihi and conservation monitoring.

Additionally, vocal individuality could be an interesting tool for studying the divergence of reintroduced hihi populations and for future hihi translocations. Over time, geographically isolated populations on the North Island may develop distinct dialects. This could lead to problems if further translocations or genetic top-ups are planned, as song divergence might reduce recognition between individuals, potentially affecting territory formation and mate choice (Lewis et al., 2021). Serial translocations – such as those from Tiritiri Matangi to mainland sanctuaries - can increase the rate of song differentiation among populations, resulting in population divergence. This pattern has been observed in other New Zealand passerines. For instance, North Island Kokako populations that were translocated have shorter and higher frequency songs and lower phrase repertoires compared to their source populations (Valderrama et al., 2012). Similarly, North Island Saddlebacks show reduced song-type sharing between translocated and ancestral populations (Parker et al., 2012). An investigation into potential dialects of hihi populations across the North Island, including comparisons with the original population on Little Barrier Island and the donor population on Tiritiri Matangi, would provide valuable insight into the cultural evolution of song and its implications for conservation management of hihi.

In conclusion, this study examined the song repertoire size, sharing, and individual distinctiveness in male hihi at Tarapuruhi Bushy Park. While vocal individuality offers great potential for monitoring and identifying individuals, challenges such as bias towards males and uncertainty about capture complete repertoires remain. The findings highlight the importance of long-term studies and the integration of automated recording technologies. Additionally, exploring the potential for identifying females through vocalizations and research into the existence of dialects will enhance the applicability of bioacoustics for hihi conservation and population management.

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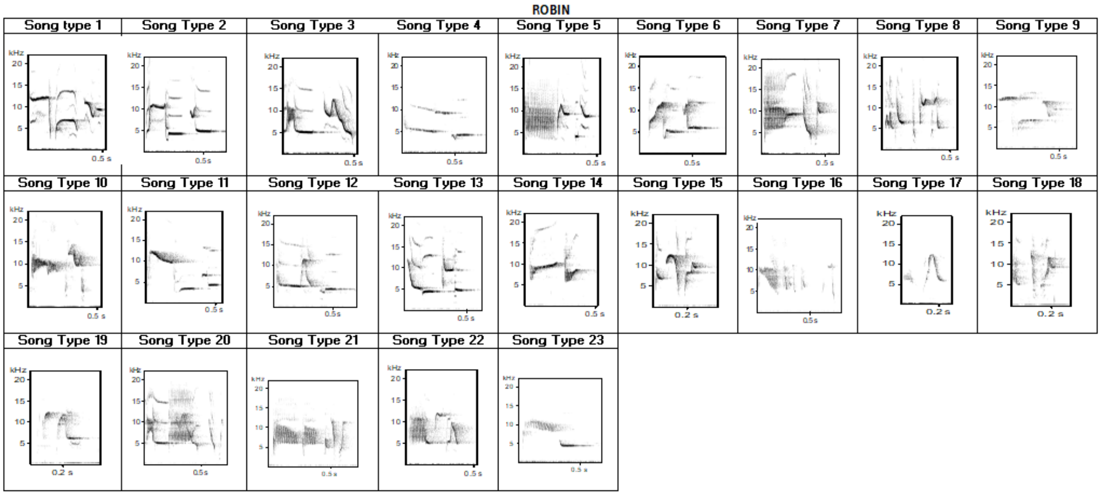
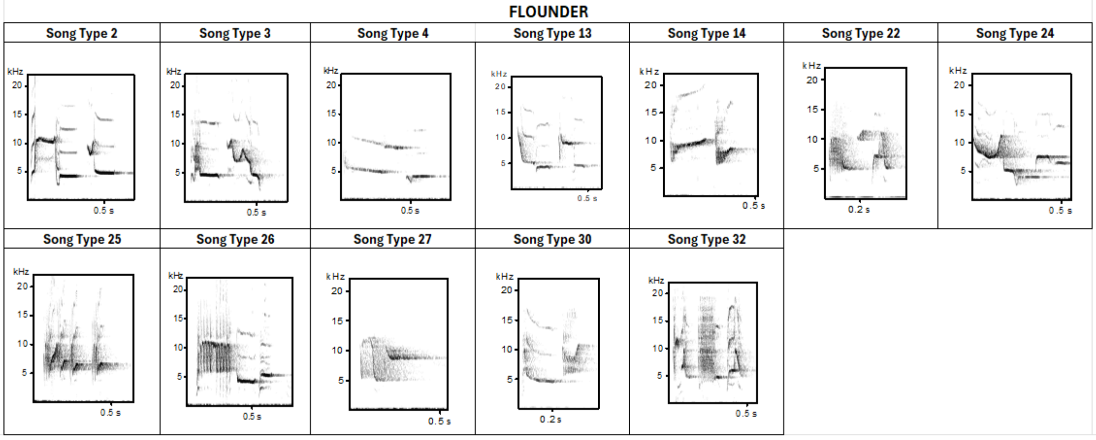
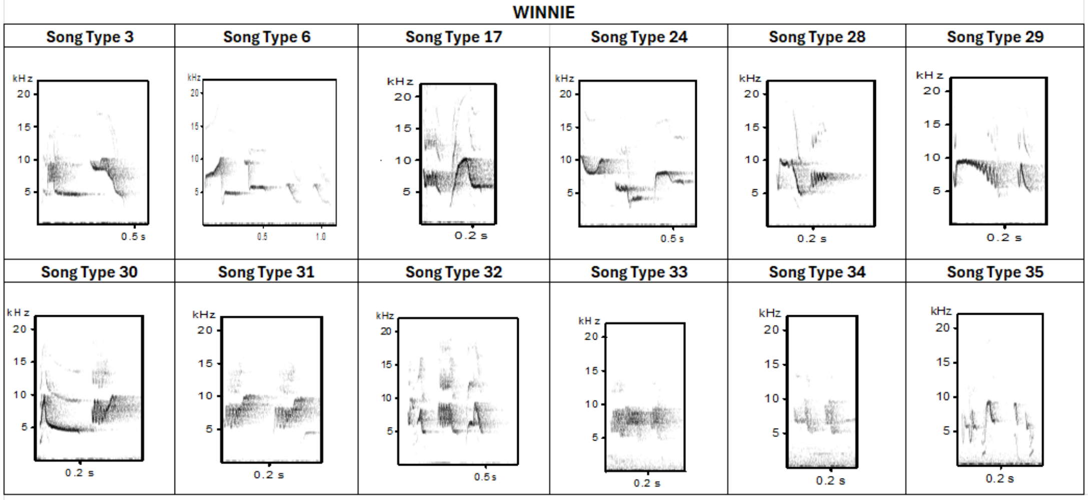
7. Appendix

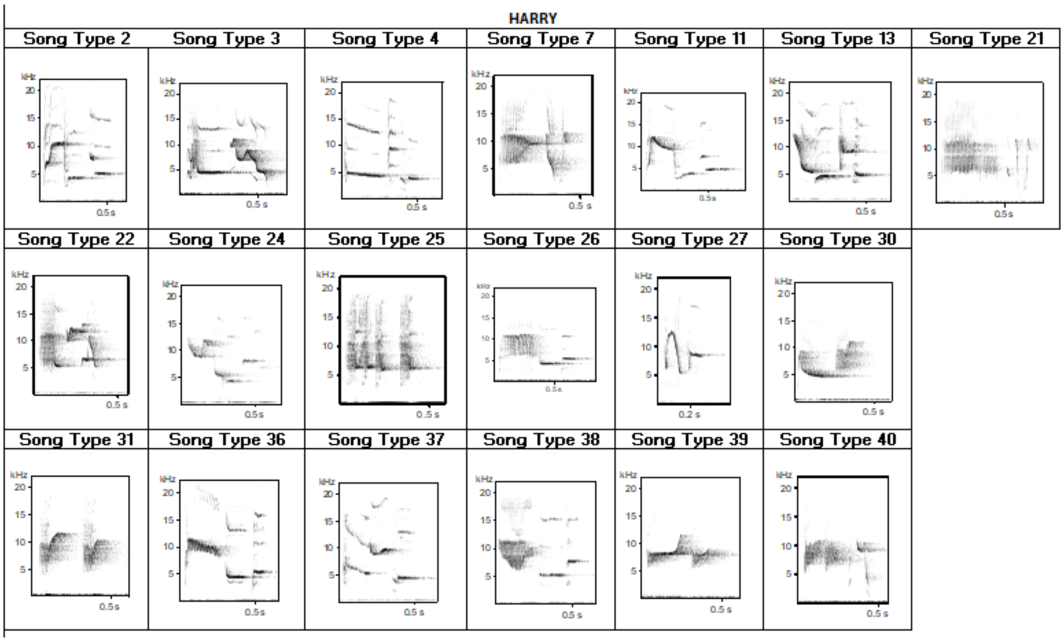
Appendix 1: Song repertoire database of all males



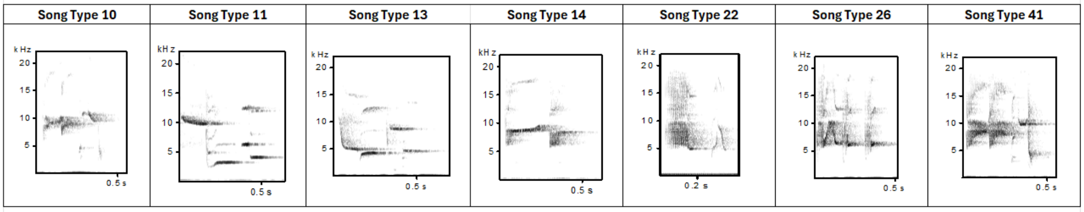




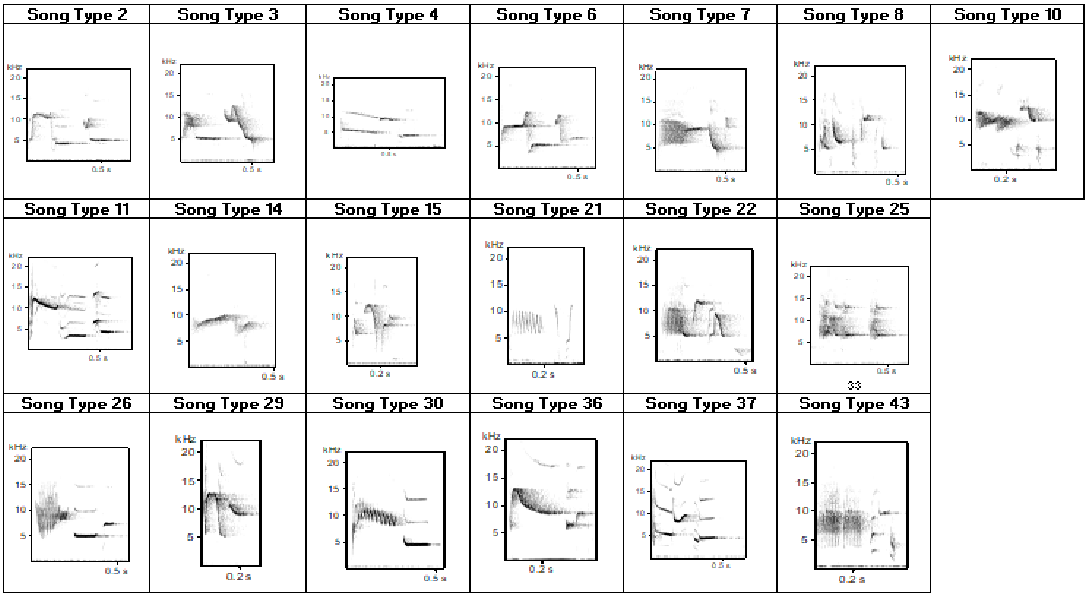
HARRY

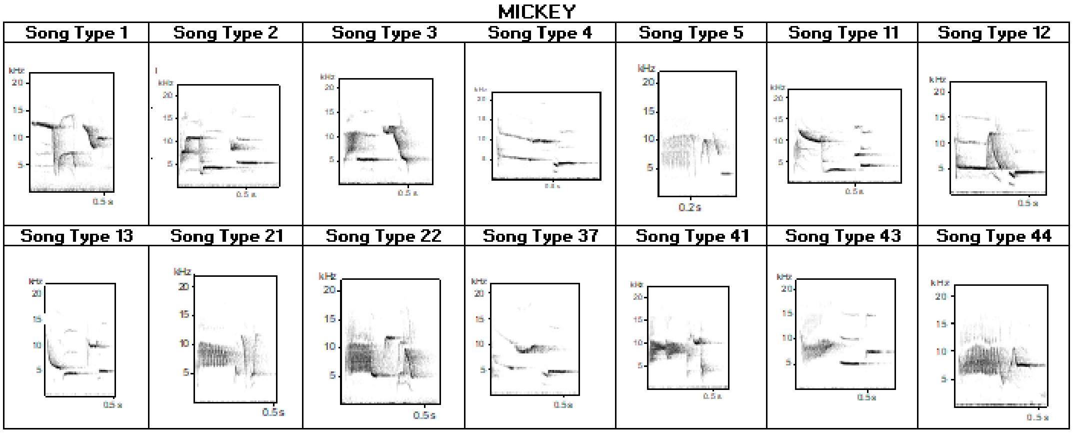


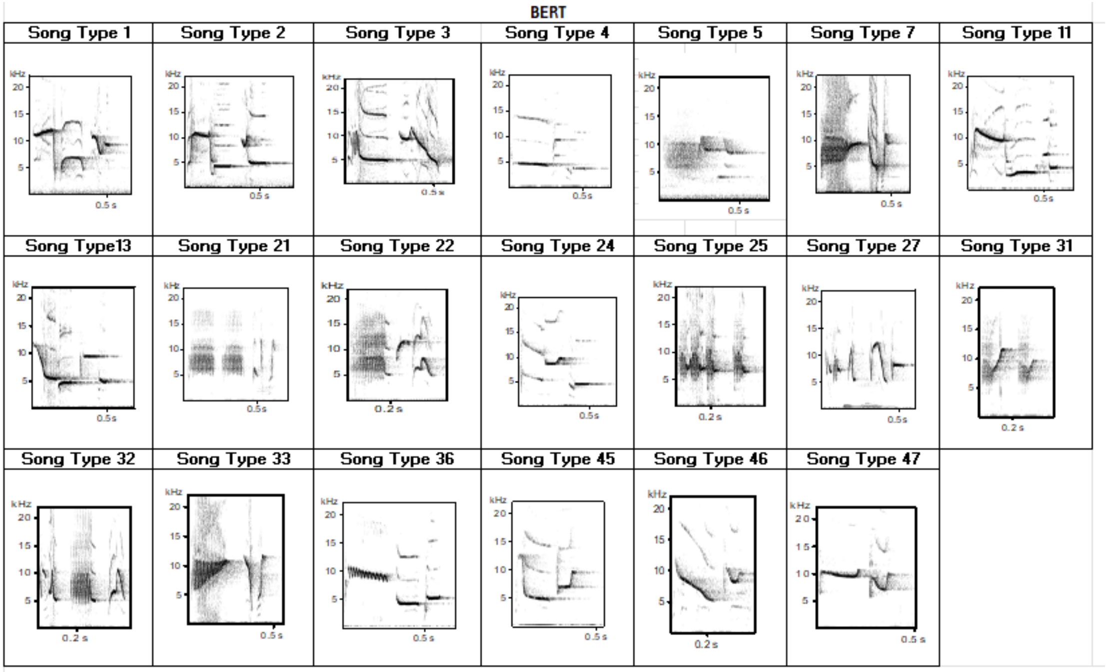
SUNNY

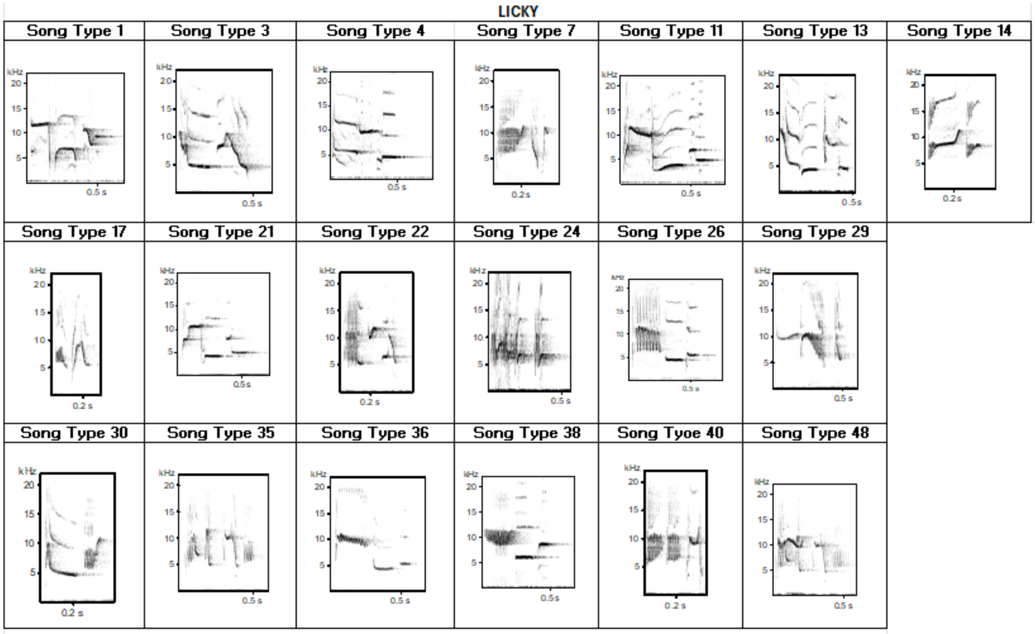


GHOST




MICKEY
Song Type 1
Song Type 2
Song Type 3
Song Type 4
Song Type 5
Song Type 11
Song Type 12
Song Type 13
Song Type 21
Song Type 22
Song Type 37
Song Type 41
Song Type 43
Song Type 44
kHz
20
15
10
5
0.5 s
0.2 s


BERT
Song Type 1
Song Type 2
Song Type 3
Song Type 4
Song Type 5
Song Type 7
Song Type 11
Song Type13
Song Type 21
Song Type 22
Song Type 24
Song Type 25
Song Type 27
Song Type 31
Song Type 32
Song Type 33
Song Type 36
Song Type 45
Song Type 46
Song Type 47
kHz
20
15
10
5
0.5 s
0.2 s


LICKY
Song Type 1
Song Type 3
Song Type 4
Song Type 7
Song Type 11
Song Type 13
Song Type 14
Song Type 17
Song Type 21
Song Type 22
Song Type 24
Song Type 26
Song Type 29
Song Type 30
Song Type 35
Song Type 36
Song Type 38
Song Tyoe 40
Song Type 48
kHz
20
15
10
5
0.5 s
0.2 s

Appendix 2: R script

2.1 R-code

“mainscript.R”

“crosscorrelation.R”

2.2 Files for R-code

“C:/Appendix/hihi_data.csv”

“C:/Appendix/recording_data.csv”

“C:/Appendix/hihipairs.csv”

“C:/Appendix/cormatrix3.csv”

“C:/Appendix/cormatrix22.csv”