生物策略表

類別	生物策略 (Strategy)
生物策略 STRATEGY	蜂鳥如何發出嗡嗡聲 (How a Hummingbird Hums)
生物系統 LIVING SYSTEM	蜂鳥 (Hummingbird)
功能類別 FUNCTIONS	# 調整壓力 (Modify pressure) # 發送聲音訊號 (Send sound pressure) # 在空中導航 (Navigate through air)
作用機制標題	蜂鳥在拍打翅膀時，無論是向下拍打還是向上拍打，都會產生升力和聲音，從而產生穩定的音樂嗡嗡聲，而不是大型鳥類的脈動呼嘯聲。 Hummingbirds produce lift and sound on both the downstroke and upstroke of their wingbeats, creating a steady musical hum instead of the pulsing whoosh of larger birds.
生物系統/作用機制示意圖 (確認版權、註明出處；畫質)	 https://images.pexels.com/photos/5090853/pexels-photo-5090853.jpeg?auto=compress&cs=tinysrgb&dpr=2&h=750&w=1260

作用機制摘要說明 (SUMMARY OF FUNCTIONING MECHANISMS)

前言

一隻蜂鳥在空中快速來回穿梭，隨後飛向一簇鮮紅的紅鳥花。牠懸停在一朵朵花前，啜飲甜美的花蜜，以補充飛行所需的能量。同時，環繞四周的是穩定而悅耳的聲音，這正是蜂鳥在英語中得名的由來。其他鳥類拍動翅膀時會產生間歇性的呼呼聲，那麼蜂鳥的嗡嗡聲又是如何產生的呢？

策略

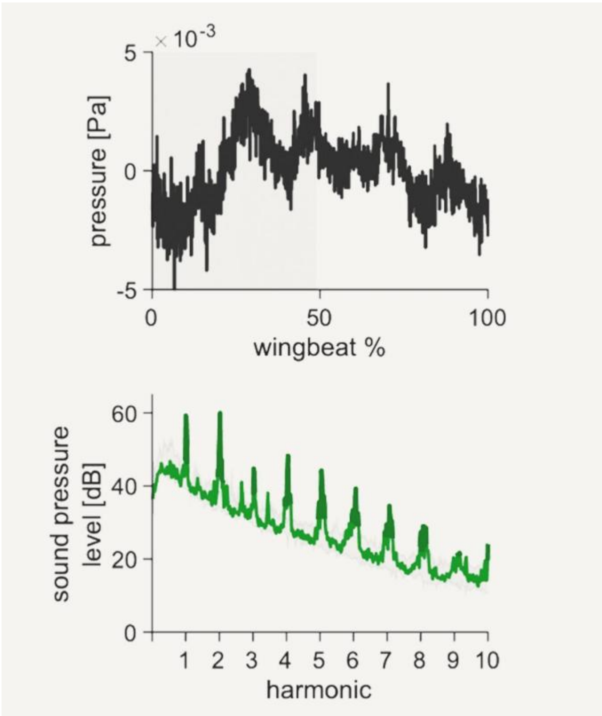
大多數鳥類的翅膀是上下拍動的——牠們在下拍時展開翅膀，向下推動空氣產生升力，而在上拍時則收攏翅膀，以減少空氣阻力，讓翅膀更輕鬆地回到高處，準備下一次下拍。這種下拍動作會產生壓力波，形成我們聽到的週期性呼呼聲。

然而，蜂鳥（以及某些昆蟲）的翅膀並不是單純上下拍動，而是以微微傾斜的角度對準地面，並以「8」字形的軌跡來回振動。這樣的動作使牠們在每一個拍動階段都能推動下

方的空氣，因此能夠像人在水中踩水一樣懸停在空中。此外，這種雙向推動空氣的方式，讓蜂鳥在每一次翅膀擺動的兩個階段都會發出聲音，形成獨特的嗡嗡聲。

「蜂鳥的翅膀就像一件經過精密調校的樂器，」史丹佛大學教授 David Lentink 說道。他與該校的科學家，以及荷蘭埃因霍溫理工大學的研究團隊，最近利用高速攝影機、壓力感測板和超過 2,000 個麥克風，來研究蜂鳥飛行如何產生這種音樂般的聲音。

他們研究了安娜蜂鳥，這種蜂鳥的翅膀振動頻率高達每秒 40 次。單純以這樣的頻率重複拍動翅膀，確實會產生聲音，但並不會呈現蜂鳥嗡嗡聲特有的變化與音樂感。而蜂鳥翅膀來回擺動所產生的交替壓力波相互作用，為聲音增添了更多層次。此外，在每個拍動循環結束時，翅膀旋轉以準備反向擺動，這一動作在各個方向上產生額外的壓力波，使蜂鳥的嗡嗡聲變得更加複雜而豐富。



請注意，單一麥克風（上方）記錄到的壓力變化頻繁且複雜。經過超過 2000 個麥克風的平均處理後，聲學頻譜（下方）顯示，前兩個諧波是等效的，並且同樣占主導地位。

長笛、小號和鋼琴都可以演奏相同的音符，但每種樂器都有其獨特的音色，稱為音質（timbre）。當樂器發出聲音時，我們的耳朵會將基頻（fundamental frequency）辨識為該音符的音高（例如「中央 C」）。然而，在這個基頻背後，還有多個以不同頻率振盪的諧波波形。儘管我們的耳朵無法單獨分辨這些諧波，但它們共同塑造了每種樂器獨特的音色，就像聲音的指紋一樣。

透過對蜂鳥飛行的詳細數據分析，科學家們建立了一套數學模型，用於描述其他鳥類和昆蟲翅膀拍動時產生的聲音。整體而言，該模型顯示，體重較重的生物會發出更響亮的

振翅聲，因為較高的升力和阻力會產生更強的壓力波。此外，在飛行過程中，不同生物為克服自身體重所需的力量，會產生不同的諧波模式，進而塑造出各自獨特的振翅音色。

潛力

翅膀振動所產生的聲音種類繁多，取決於拍動的是哪種鳥類或昆蟲。一些昆蟲利用翅膀聲吸引配偶，而某些鳥類則可能藉由拍翅頻率來判斷同伴的速度與位置。部分蜂鳥甚至能僅憑嗡嗡聲識別同種個體。然而，人為產生的噪音過大，可能會干擾這些自然交流系統。

研究蜂鳥翅膀振動所產生的特殊諧波層次，或許能為調控各類聲音提供新的見解。例如，讓船舶引擎、汽車與無人機的運作聲更安靜、更不干擾環境，從而減少噪音污染。透過這類創新技術，我們或許能創造更多機會，讓人類（以及其他蜂鳥）能夠清楚聆聽蜂鳥特有的嗡嗡聲。

Introduction

A hummingbird flits back and forth before flying up to a cluster of bright red cardinal flowers. As it levitates in front of one bloom after the other sipping sweet nectar to replenish the calories it needs to fly, it's accompanied by the steady, pleasant sound that gives the bird its name in English.

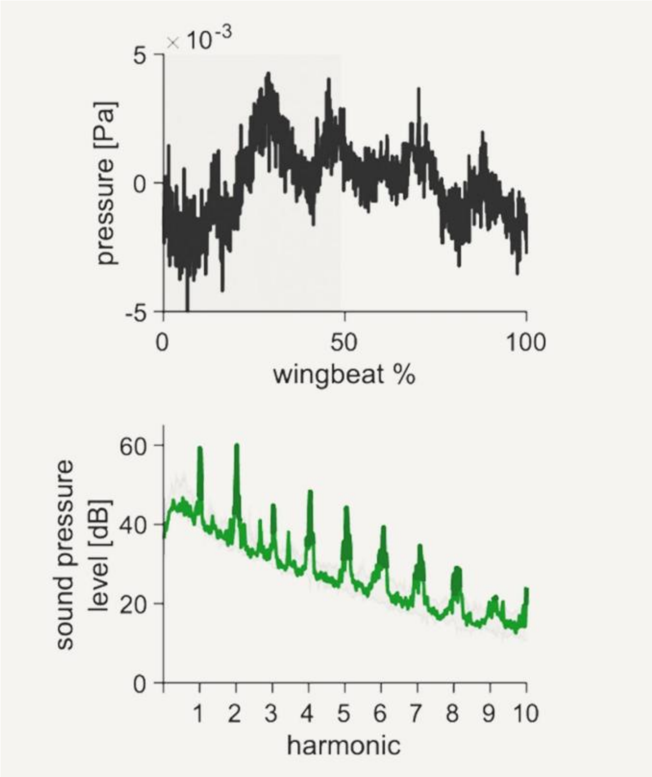
Other birds create a periodic *whoosh* sound with every flap of their wings. What gives the hummingbird its hum?

The Strategy

Most birds flap their wings up and down—opening up on the downstroke to push against the air below, and tucking in on the upstroke to decrease resistance and more easily return to a high point to push down again. The downstroke creates a pressure wave, and that's what we hear as the periodic woosh. Hummingbirds (and insects) don't flap up and down. They hold their wings angled to the ground and flap them back and forth in a figure-8 pattern. This pushes against the air below during both parts of the stroke, enabling them to hover in place (like a human treading water) and producing a sound on both halves of the stroke.

"A hummingbird wing is similar to a beautifully tuned instrument," says professor David Lentink. Scientists working with him at Stanford University and colleagues at the Eindhoven University of Technology recently used high-speed cameras, pressure plates, and over 2,000 microphones to understand how hummingbird flight creates such a musical sound.

They studied Anna's hummingbirds, which flap their wings at the high rate of 40 beats per second. A simple repetition of a beat at that frequency would create a sound, but not one with the variability and musicality of the hummingbird's hum. The alternating pressure waves of the back-and-forth stroke though interact with each other, creating more layers to the sound. Even more complexity is added by the pressure waves created in all directions when the wings rotate at the end of each half of the stroke to head back in the other direction.



Notice the many fluctuations in pressure as recorded from a single microphone (top). The resulting harmonics in the acoustic spectrum averaged across all of the more than 2000 microphones (bottom) show that the first two are equivalent and both are dominant.

A flute, trumpet, and piano can all play the same note, but each has a characteristic sound called timbre. When an instrument makes a sound, your ears hear the fundamental frequency as the pitch of the note (such as "middle C"). But behind the first harmonic wave are multiple other waves oscillating at different frequencies. Though your ear doesn't distinguish them individually, together they produce the specific timbre for each source—the sound-equivalent of a fingerprint.

From the detailed information gathered from the hummingbirds, the scientists developed a mathematical model to characterize the sound of wings flapping in other birds and insects. In general, their model showed that heavier body weights translated to louder wing sounds because the higher lift and drag generated stronger pressure waves. The forces needed to overcome different body weights during flight also resulted in varied harmonic patterns that contributed to the unique wing-flapping timbre for each organism.

The Potential

Wings make an array of noises, depending on what bird or insect is doing the flapping. Some insects use wing noises to attract mates while some birds may interpret flapping frequencies to understand the speed and position of other members of their flock. Some hummingbirds may recognize members of their species solely by hearing their hums. Overpowering human-generated noise can disrupt any of these natural systems.

Learning from the specific harmonic layering produced by hummingbird wing strokes may provide insights on how to alter sounds of all kinds. Quieter or less distracting ship motors, cars, and flying drone vehicles could go a long way to reducing damaging noise pollution. Through such innovations, we might even produce more opportunities for people (and other hummingbirds) to hear a hummingbird's hum.

文獻引用 (REFERENCES)

「鳥類、蝙蝠和昆蟲通過拍動翅膀產生不穩定的空氣動力，從而提升身體進入空中，使其能夠飛行。當翅膀在空氣中振動時，會產生不穩定的壓力波動，並以音速向外傳播。除了提供飛行能力外，這些壓力波還在行為展示中發揮多種聲學傳遞功能。」

"Birds, bats, and insects flap their wings to generate unsteady aerodynamic forces that lift their body into the air, which enables them to fly. When their flapping wings move through air, they create unsteady pressure fluctuations that radiate outward at the speed of sound. In addition to furnishing flight, pressure waves serve various acoustic communication functions during behavioral displays."

參考文獻清單與連結 (REFERENCE LIST) **Harvard 或 APA 格式**

鳥類是演化上的工程奇蹟。牠們源自恐龍，但與我們印象中厚重、多鱗的爬行動物大相逕庭。在使鳥類與眾不同的特化適應中，最顯著的便是飛行——儘管某些哺乳動物也能飛行，但鳥類無疑是空中數量最多的族群。許多鳥類擁有中空且輕盈的骨骼，以及特化的翅膀，使牠們能夠在空中翱翔。此外，牠們的羽毛由角蛋白構成，不僅能保暖，還能吸引配偶，並提升飛行時的導航與空氣動力效應。與牠們的恐龍祖先相比，鳥類已不再擁有真正的牙齒，而是以特化的喙來取而代之。

"Birds, bats, and insects flap their wings to generate unsteady aerodynamic forces that lift their body into the air, which enables them to fly. When their flapping wings move through air, they create unsteady pressure fluctuations that radiate outward at the speed of sound. In addition to furnishing flight, pressure waves serve various acoustic communication functions during behavioral displays."

[How Oscillating Aerodynamic Forces Explain the Timbre of the Hummingbird's Hum and Other Animals in Flapping Flight]   Hightower, B. J., Wijnings, P. W., Scholte, R., Ingersoll, R., Chin, D. D., Nguyen, J., ... & Lentink, D. (2021). How oscillating aerodynamic forces explain the timbre of the hummingbird's hum and other animals in flapping flight. *Elife*, *10*, e63107.
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生物系統延伸資訊連結 (LEARN MORE ABOUT THE LIVING SYSTEM/S)
撰寫/翻譯/編修者與日期
張睿庭翻譯 (2025/03)；許秋容編修 (2024/4/09)
AskNature 原文連結
https://asknature.org/strategy/wings-produce-a-musical-hum/