

# Birds sing at a higher pitch in urban noise

Great tits hit the high notes to ensure that their mating calls are heard above the city's din.

The ongoing spread of urban areas, highways and airports throughout the world makes anthropogenic noise almost omnipresent. We have found that urban great tits (*Parus major*) at noisy locations sing with a higher minimum frequency, thereby preventing their songs from being masked to some extent by the predominantly low-frequency noise. They have presumably learned selectively from a restricted range of their repertoire — a behavioural plasticity that may be critical for breeding success in a noisy world.

Cars, planes and all sorts of machinery create a new selection pressure on wildlife species that use acoustic signals to achieve reproductive success. This might create two groups of species: one that can adapt their signals to the competing noise, and another that cannot. Although there is a decline in species density and diversity associated with sprawling cities and highways<sup>1–4</sup>, there is no evidence yet for a direct role of sound pollution<sup>5,6</sup>, nor is there much insight into how successful urban species cope under noisy circumstances<sup>7,8</sup>.

We investigated an urban population of great tits in the Dutch city of Leiden. Noise-amplitude measurements, taken with a sound-pressure meter, varied markedly between territories. Mean amplitude levels per territory ranged from 42 to 63 decibels, from very quiet in residential areas to extremely noisy near a highway or a busy crossing. We used a highly directional microphone for song recordings and an omnidirectional microphone for independent noise recordings at a height of 5 m. The spectral composition of ambient noise was generally characterized by loud, low-frequency sounds.

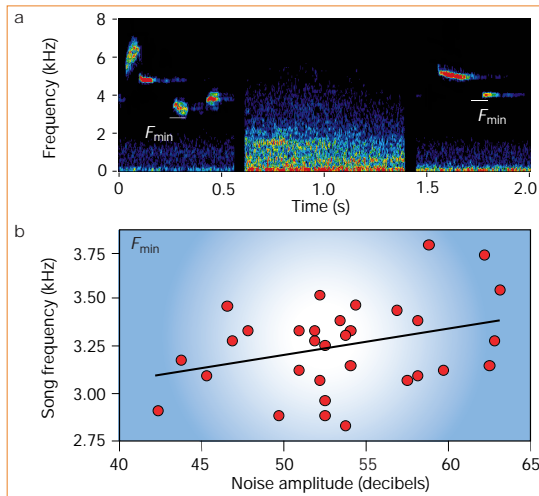
We compared noise amplitude with the spectral distribution of sound energy within the range of the minimum frequency of great-tit song and found that in noisy territories there is a greater proportion of sound energy in the lower half of this range than in quiet territories (Pearson's  $r = 0.78$ ,  $P < 0.001$ ).

We measured the acoustic characteristics of 32 male great tits, each of which had a repertoire of between three and nine distinct song types. Mean song frequencies varied considerably between individual birds. The average minimum frequency ranged from 2.82 to 3.77 kHz and was significantly correlated with ambient noise (multiple regression:  $n = 32$ , d.f. = 2,  $F = 4.74$ ,  $P = 0.017$ ), with regard to both amplitude level ( $t = 3.02$ ,  $P = 0.005$ ) and spectral distribution ( $t = -2.0$ ,  $P = 0.055$ ). Noisy territories were home to great-tit males whose songs had a high average minimum frequency. Birds in quiet territories sang more notes that reached the lowest frequencies

measured for the population (Fig. 1). It is possible that individuals with genetically predetermined song spectra could end up in matching territories with regard to noise spectra through a process of trial and error. But we know that great tits learn their song and that major adjustments occur in their breeding territory during interactions with neighbours<sup>9</sup>. Hence it is more likely that they learn to use a restricted range of their spectral capacity in response to frequency-dependent interference from local noise conditions — adjusting song to territory instead of territory to song.

Frequency use by great tits is also known to vary with sound-transmission properties in different habitats<sup>10</sup>, and correlations with natural ambient-noise spectra are found in other birds<sup>11,12</sup>. Local song adjustment within the heterogeneous urban habitat, as we find here, might indicate that habitat-wide adjustment through song learning may also contribute to acoustic divergence at the population level<sup>12,13</sup>.

Our findings show, to our knowledge for the first time, that human-altered environments might change the communication signals of a wild bird species<sup>5</sup>. The apparent song plasticity of great tits may represent a



general behavioural mechanism that allows more bird species to reproduce despite high noise levels. Species that lack such learning plasticity after dispersal to the breeding territory, or have no room for variation within the conspecific frequency range, might suffer from auditory masking. For those species, anthropogenic noise could affect breeding opportunities and contribute to a decline in species density and diversity.

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## Fluid dynamics

### Vortex rings in a constant electric field

Despite nearly two centuries of study, the response of colloidal suspensions to electric fields can be surprising, particularly if the suspended particles also interact with each other. We describe a previously unrecognized class of hierarchically organized dynamic patterns that arises in aqueous

charge-stabilized colloidal suspensions when electrohydrodynamic forces due to constant applied fields compete with gravity.

Our system (Fig. 1a) consists of an aqueous suspension of monodisperse colloidal silica spheres 3.0  $\mu\text{m}$  in diameter (Bangs Labs, lot no. 4740), confined to a thin horizontal layer between a glass coverslip and a microscope slide. Both inner surfaces are coated with 10-nm-thick gold electrodes on 10-nm-thick titanium wetting layers. Although still optically thin, these electrodes have a resistivity

of less than 50 ohms per square and allow us to apply uniform vertical electric fields to the confined suspension. Once equilibrated in air to pH 5.5, the silica spheres develop a surface charge density of  $-0.4 \text{ mC m}^{-2}$  (ref. 1). As their density is  $2 \text{ g cm}^{-3}$ , they sediment rapidly onto the lower electrode.

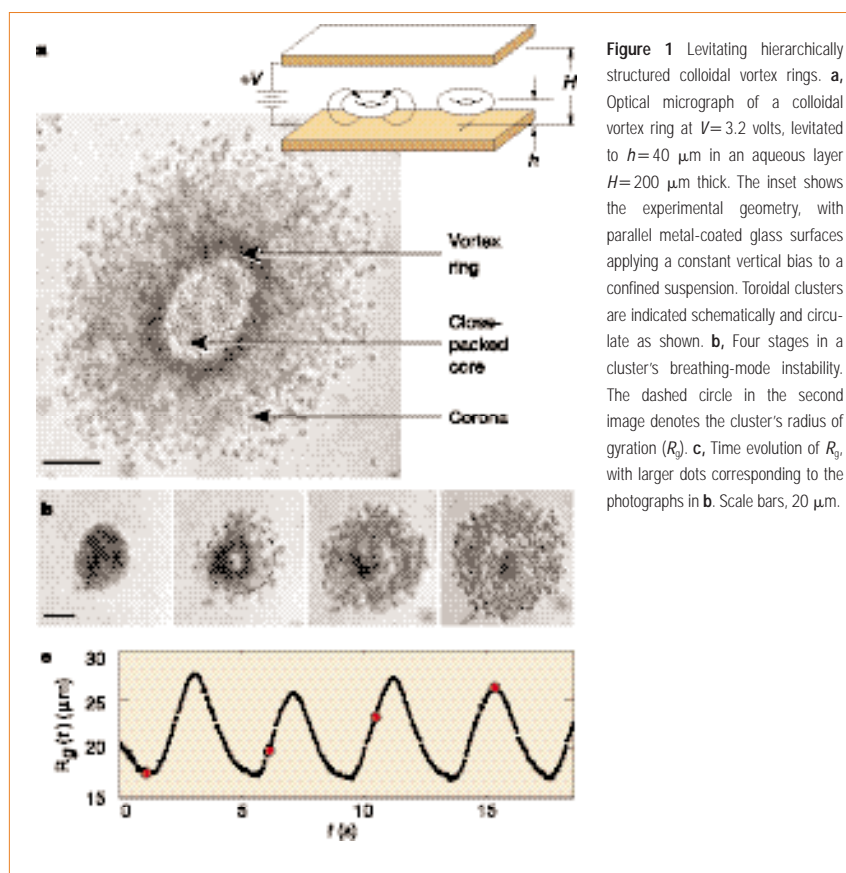
Ions in solution screen out the electric field for biases below 2.4 V. Sustained upward forces occur only at higher biases for which hydrolysis at the electrodes feeds steady-state ionic fluxes, which in turn exert electroviscous forces on the charged spheres<sup>2,3</sup>. These fluxes are spatially uniform in the parallel plate geometry, so that the force on an isolated sphere is independent of height  $h$ . Consequently, well-separated spheres (less than 0.01 monolayer) rise straight to the upper electrode at biases high enough to overcome gravity.

Distortions in the ionic fluxes due to the charged spheres mediate long-range interactions between spheres<sup>2</sup>, which can induce interesting cooperative behaviour. In suspensions forming more than a monolayer, the spheres are levitated by biases exceeding 2.6 V into hundreds of flower-like clusters such as the example in Fig. 1a, all floating at  $h = 40 \mu\text{m}$ . Each cluster consists of a toroidal vortex in which spheres travel downwards along the inside and return upwards along the outside, completing one cycle in a few seconds. Most are surrounded by diffuse circulating coronas extending outwards for tens of micrometres. The clusters' circulation is consistent with a central downward flux of hydronium ions surrounded by an upward-moving sheath of hydroxyl ions, the resulting charge separation being supported by the spheres' charges and excluded volumes<sup>2,3</sup>. However, this does not seem to explain all of the clusters' features.

Many circulating clusters enclose colloidal crystals<sup>4</sup>, most of which are monolayers. These close-packed domains disperse immediately once the driving field is turned off. Consequently, each cluster seems to straddle a stagnation plane, quite unlike a conventional vortex ring<sup>5</sup>.

Individual clusters sometimes develop breathing-mode instabilities with periods of a few seconds. One oscillating cluster's radius of gyration is tracked in Fig. 1b, c. Remarkably, the cluster's crystalline core reforms with each cycle. The oscillations of neighbouring clusters do not become phase-locked, and steadily circulating clusters can coexist with oscillating clusters. Consequently, distortions in the ionic fluxes entrained by a cluster seem to be well localized.

Clusters drift freely across the field of view, and so do not form at defects in the electrodes. Substantially smaller silica spheres do not form rings, but instead rise directly to the upper electrode, where they form interfacial crystals<sup>2,6</sup>, as do less dense polystyrene and poly-(methyl methacrylate) spheres. So we conclude that colloidal vortex rings emerge as a cooperative phenomenon



**Figure 1** Levitating hierarchically structured colloidal vortex rings. **a**, Optical micrograph of a colloidal vortex ring at  $V=3.2$  volts, levitated to  $h=40 \mu\text{m}$  in an aqueous layer  $H=200 \mu\text{m}$  thick. The inset shows the experimental geometry, with parallel metal-coated glass surfaces applying a constant vertical bias to a confined suspension. Toroidal clusters are indicated schematically and circulate as shown. **b**, Four stages in a cluster's breathing-mode instability. The dashed circle in the second image denotes the cluster's radius of gyration ( $R_g$ ). **c**, Time evolution of  $R_g$ , with larger dots corresponding to the photographs in **b**. Scale bars,  $20 \mu\text{m}$ .

driven both by electrokinetic forces and by gravity. Understanding their origin could lead to new methods for creating opals of technologically relevant materials.

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#### COMMUNICATIONS ARISING

#### Development rate

### Modelling developmental time and temperature

The rate at which ectothermic animals develop is sensitive to temperature. Gillooly *et al.*<sup>1</sup> suggest that the magnitude of the effect of temperature on the rate of development is roughly the same at all life stages and for all species. In reality, different life stages and different species vary

considerably in terms of their sensitivity to changes in the thermal environment. This variability means that universal models based on cross-stage and cross-species comparisons, such as that proposed by Gillooly *et al.*, are of limited use in predicting how populations of animals will respond to temperature change.

The effect of temperature on development rate varies significantly during the course of development. For example, van't Hoff  $Q_{10}$  values for the duration of defined embryonic stages vary from 2.0 to 12.0 in the tailed frog *Ascaphus truei*<sup>2</sup> (interval  $Q_{10}$ ; Fig. 1a). (The van't Hoff  $Q_{10}$  is a simple indicator of thermal sensitivity based on the assumption of an exponential relationship between rate and temperature. A  $Q_{10}$  of 2.0 means that the rate doubles for each rise in temperature of  $10^\circ\text{C}$ ; a  $Q_{10}$  of 12.0 indicates that the rate increases 12-fold.)

Van't Hoff  $Q_{10}$  values for the duration of defined embryonic stages range from 1.9 to 8.2 in chinook salmon *Oncorhynchus tshawytscha*<sup>3</sup> (Fig. 1b) and from 2.2 to 5.8 in the sea urchin *Strongylocentrotus droebachiensis*<sup>4</sup> (Fig. 1c). The degree of variation is similar if the slope function,  $\alpha$ , of Gillooly *et al.*, rather than the van't Hoff  $Q_{10}$ , is used to estimate thermal sensitivity. For example, values of  $\alpha$  for the tailed frog range from  $-0.075$  to  $-0.27$ , equivalent to Arrhenius  $Q_{10}$  values of 2.1 to 14.9 (Arrhenius