conclusively determined, but several possible models could account for this delay. The difference in timing may be related to a variability in the subsurface stratigraphy and/or to liquefaction in more than one layer. Conditions may have been such that a relatively impermeable layer allowed the development of a pressure head that was ultimately released explosively, giving rise to the craters (deeper and thinner clay layers develop greater maximum hydraulic gradients[4]). Dry craters would be generated by the release of large bubbles of gas, perhaps as a result of aggregative fluidization[2] or of the collapse of a gas-filled cavity at depth soon after liquefaction occurred, which would force gas to the surface.

The severity of ground failure as a result of liquefaction is related to site conditions, ground motions and distance from the epicentre[5]. In general, Bhuj's liquefaction features decrease in size with increasing epicentral distance. However, some of the largest features occur west of the fault rupture, possibly as a result of western directivity of seismic energy[1,6]. As-yet-unknown soil conditions and ground motions at the site are required to model the liquefaction potential, for which the subsurface pressure estimated here could prove a key parameter.

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Acoustics

Tuning of vocal tract resonance by sopranos

Sopranos can sing at frequencies that are rather higher than the normal values for the lowest resonance of their vocal tract, but failure to use this resonance would reduce both their vocal power and homogeneity in timbre. We have directly measured the resonance frequencies of the vocal tract of sopranos during singing, and find that, towards the top of their range, they consistently increase the frequency of the lowest resonance to match that of their singing. This significantly increases the loudness and the uniformity of tone, albeit at the expense of comprehensibility.

The different vowel sounds in normal speech are produced by adjusting the position of the tongue, jaw and lips so that the vocal tract resonates at certain specific frequencies (Ri). The vocal folds vibrate at the pitch frequency, f_0, which is usually lower than the Ri. Those harmonics of f_0 that fall near the Ri produce associated peaks, or formants (Fi), in the speech spectrum[1]. To oversimplify a little, in Western languages vowels occupy characteristic positions on a 'map' of ($F2,F1$) or ($R2,R1$).

Singers who are trained in the Western classical tradition need to make themselves heard in large auditoria, sometimes with loud accompaniment. In the high soprano range, f_0 enters the range at which human hearing sensitivity is greatest, so tuning $R1$ to match f_0 is a possibility that could produce a sound with a loudness and timbre that vary less with pitch, and which is louder for constant effort[2,3]. As vowel identifiability is inevitably compromised when f_0 greatly exceeds $R1$, this further loss of comprehensibility is tolerable. Indeed, sopranos are often taught to lower
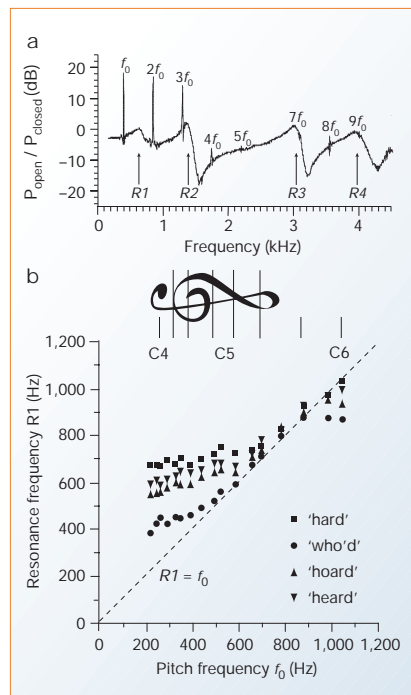
Figure 1 Simultaneous measurements of the resonance frequencies of the vocal tract and the harmonics present in the voice signal. **a**, The ratio of the spectrum measured with the mouth open, to that with the mouth closed (P_{open}/P_{closed}) when the vowel in the word 'hard' is sung at A4. Several harmonics of the voice signal with fundamental frequency $f_0 = 440$ Hz can be seen. The maxima in the broad band signal corresponding to the resonances $R1$, $R2$, $R3$ and $R4$ are indicated by arrows. **b**, The lowest resonance frequency, $R1$, as a function of the pitch frequency f_0. The pitch is indicated in musical terms by the rotated treble clef at the top of the figure.

the jaw or to 'smile' as they ascend a scale; both of these actions increase mouth opening, which in turn increases $R1$ (refs 4, 5).

We measured the resonances of the tract directly by using a previously described technique[6,7]. Briefly, an acoustic current source (diameter, 10 mm), synthesized from frequencies spaced at 5.38 Hz over the range 0.2–4.5 kHz, and a microphone (diameter, 8 mm) are placed just below the singer's mouth, in contact with the lower lip. The acoustic current is adjusted so that the pressure spectrum, P_{closed}, is independent of frequency when the singer's mouth is closed. The ratio of the spectrum measured with the mouth open to that with the mouth closed shows peaks that indicate the resonances of the tract[6] as well the harmonics present in the voice signal (Fig.1a). The shift in resonance frequency due to the reduction in area for radiation caused by the presence of the apparatus lay within the resolution of these experiments (± 11 Hz).

Eight sopranos (four professional, four advanced students), with an average of nine years' classical training, sang notes sustained for 4 s without vibrato in an ascending diatonic scale indicated by a glockenspiel before each note. They sang one of four vowels presented in writing in the form 'h<vowel>d' ('hard', 'hoard', 'who'd', 'heard'). They sang *piano* (softly) to avoid saturating the microphone and to improve the signal-to-noise ratio.

When f_0 was less than the value of $R1$ for normal speech, the resonance for each vowel was roughly constant (Fig. 1b). This is consistent with expectations, as ($R1,R2$) characterizes vowels. However, when f_0 exceeded this value of $R1$, the tuning line $R1 = f_0$ was followed. This trend continued to 1 kHz for the vowels that do not use lip rounding ('hard', 'heard'), but for the vowels that use lip rounding ('hoard', 'who'd'), the data fell below the tuning line near 1 kHz. This may be because, with the lips rounded, it is uncomfortable or anatomically impossible to raise $R1$ to 1 kHz.

This large shift in $R1$ at high pitch means not only that vowels are shifted significantly on the vowel plane, but also that they will overlap considerably and converge to separations that are smaller than the characteristic length, λ, at which they become confused with one another[6]. This helps to explain the well-known difficulty in identifying words sung in the high range by sopranos[8,9], and may be one of the reasons why opera houses often use surtitles even for operas sung in the native language of their audience.

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