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1. Collinge, J., Sidle, K. C. L., Meads, J., Ironside, J. & Hill, A. F. *Nature* **383,** 685–690 (1996).
2. Hill, A. F. *et al. Nature* **389,** 448–450 (1997).
3. Bruce, M. E. *et al. Nature* **389,** 498–501 (1997).
4. Collinge, J. *Lancet* **354,** 317–323 (1999).
5. Hill, A. F. *et al. Lancet* **353,** 183–189 (1999).
6. Wadsworth, J. D. F. *et al. Lancet* **358,** 171–180 (2001).
7. Montrasio, F. *et al. Science* **288,** 1257–1259 (2000).
8. Collinge, J., Palmer, M. S. & Dryden, A. J. *Lancet* **337,** 1441–1442 (1991).
9. Palmer, M. S., Dryden, A. J., Hughes, J. T. & Collinge, J. *Nature* **352,** 340–342 (1991).
10. Bunce, M. *et al. Tissue Antigens* **46,** 355–367 (1995).

Brazil-nut effect

Size separation of granular particles

Granular media differ from other materials in their response to stirring or jostling — unlike two-fluid systems, bi-disperse granular mixtures will separate according to particle size when shaken, with large particles rising, a phenomenon termed the 'Brazil-nut effect'[1–8]. Mounting evidence indicates that differences in particle density affect size separation in mixtures of granular particles[9–11]. We show here that this density dependence does not follow a steady trend but is non-monotonic and sensitive to background air pressure. Our results indicate that particle density and interstitial air must both be considered in size segregation.

Explanations of the Brazil-nut effect, which has been known since the 1930s, have focused either on infiltration of small particles into voids created underneath larger ones during shaking[1–5] or on granular convection[6–8], and have implied density-independent rising times for the larger 'intruder' particles. However, an increase in the velocity of a large intruder with increasing density has been reported[9,10], suggesting that increased inertia might play a role. Furthermore, in computer simulations[10], a 'reverse' Brazil-nut effect was found, in which groups of larger particles, if heavy enough, segregate to the bottom.

A monotonic density dependence implied by such mechanisms[9–11] is incompatible with our measurements of intruder rising times over a wide range of size and density ratios (Fig. 1). We tracked an intruder particle in the presence of granular convection produced by vertically shaking a three-dimensional cylinder filled with smaller background particles (density, ρ_m). A spherical intruder (diameter, D; density, ρ) was placed at a depth z_0 below the surface; a hollow acrylic ball filled with foam and lead shot was used to tune the intruder density. Material properties other than density, such as coefficients of restitution and friction, had no measurable impact.

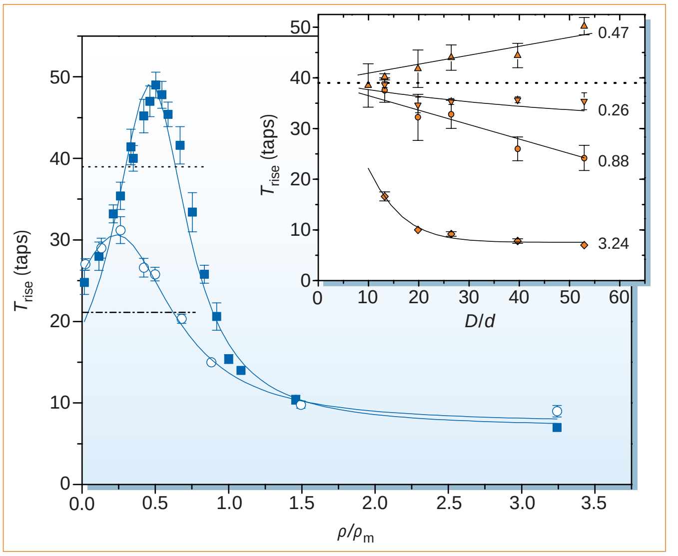

Figure 1 Density and size dependence of the Brazil-nut effect. The rising time, T_{rise}, of a spherical intruder of density ρ and diameter D, starting with its top at a depth $z_0=4.6$ cm below the surface of a vibrated granular medium consisting of $d=0.5$ mm glass spheres ($\rho_m=2.4$ g ml^{-1}), is plotted as a function of density ratio, ρ/ρ_m, and size ratio, D/d. Data were obtained using well-separated sinusoidal taps at normalized accelerations $\Gamma=A(2\pi f)^2/g=5$, where A is the shaking amplitude, f is the frequency (13 Hz) and g is the Earth's acceleration (9.81 m s^{-2}). The fill height of the container was 8.6 cm; results were similar at greater filling heights. The container diameter was 8.2 cm. A layer of glass beads, attached to the inside wall using epoxy adhesive, induces a stable, reproducible and axially symmetric convection with well-established properties[6,7,13]. Results are shown (main panel) for fixed $D=2.54$ cm at ambient pressure (squares) and $P=90$ torr (circles). Dotted and dot-dashed lines show T_{rise} for tracer particles at the respective pressures in the absence of an intruder. Inset, size dependence for intruders made from four different materials (top to bottom: nylon, wood, Teflon, steel) at ambient pressure, with the densities, ρ/ρ_m, indicated to the right of the respective traces. Solid lines in the main panel are lorentzian fits, intended as visual guides.

For a fixed intruder diameter, the measured rising time, T_{rise}, to the free surface exhibits a pronounced peak as a function of ρ/ρ_m (Fig. 1). This peak is not affected by variations in shaking parameters, background medium (glass beads, poppy seeds) and system size. Compared with convection measured in the absence of an intruder (dotted line), the intruder rises faster both at large and small ρ/ρ_m, but more slowly when $\rho/\rho_m\approx0.5$. A monotonic dependence, $T_{rise}\approx(\rho/\rho_m)^{-1/2}$, proposed for a two-dimensional system[10], is incompatible with our data. The presence of a large intruder perturbs the convective flow of the background particles. Data above the horizontal dotted lines in Fig. 1 therefore do not necessarily imply sinking intruders[9] in the absence of convection. The peak in T_{rise} becomes significant for diameter ratios $D/d>10$, increasing with increasing intruder size (Fig. 1, inset).

Measurements of intruder velocity as a function of depth show that the increase in T_{rise} with ρ/ρ_m to the left of the peak is caused by behaviour that takes place as the particle approaches the upper surface. Deeper inside the pile, T_{rise} decreases monotonically with ρ/ρ_m. The peak is sensitive to the background air pressure, P, in the cylinder. It decreases in magnitude and shifts to lower ρ/ρ_m with decreasing P, and vanishes as P approaches 1 torr. At this low pressure, the intruder velocity (both at the surface and within the bulk) no longer depends on ρ/ρ_m and coincides, within our resolution, with the non-zero convection velocity of the background particles in the absence of the intruder.

Our results indicate an intricate interplay between vibration-induced convection and fluidization, drag by interstitial air[12], and intruder motion. The rising time of a large intruder in a bed of smaller particles emerges as a sensitive probe of these interactions. Understanding the phenomenon described here may require a new approach that describes intruder motion in the presence of two 'fluids': background particles and interstitial air.

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1. Rosato, A., Strandburg, K. J., Prinz, F. & Swendsen, R. H. *Phys. Rev. Lett.* **58,** 1038–1040 (1987).
2. Jullien, R. & Meakin, P. *Nature* **344,** 425–427 (1990).
3. Jullien, R. & Meakin, P. *Phys. Rev. Lett.* **69,** 640–643 (1992).
4. Williams, J. C. *Powder Technol.* **15,** 245–251 (1976).
5. Duran, J., Rajchenbach, J. & Clement, E. *Phys. Rev. Lett.* **70,** 2431–2434 (1993).
6. Knight, J. B., Jaeger, H. M. & Nagel, S. *Phys. Rev. Lett.* **70,** 3728–3731 (1993).
7. Knight, J. B. *et al. Phys. Rev. E* **54,** 5726–5738 (1996).
8. Cooke, W., Warr, S., Huntley, J. M. & Ball, R. C. *Phys. Rev. E* **53,** 2812–2822 (1996).
9. Shinbrot, T. & Muzzio, F. J. *Phys. Rev. Lett.* **81,** 4365–4368 (1998).
10. Liffman, K., Muniandy, K., Rhodes, M., Gutteride, D. & Metcalfe, G. A. *Granular Matter* (in the press).
11. Hong, D. C., Quinn, P. V. & Luding, S. *Phys. Rev. Lett.* **86,** 3423–3426 (2001).
12. Pak, H. K., van Doorn, E. & Behringer, R. P. *Phys. Rev. Lett.* **74,** 4643–4646 (1995).
13. Ehrichs, E. E. *et al. Science* **267,** 1632–1634 (1995).