

BRIEF COMMUNICATIONS

Floater clustering in a standing wave

Capillarity effects drive hydrophilic or hydrophobic particles to congregate at specific points on a wave.

How do waves affect the distribution of small particles that float on water? Here we show that drifting small particles concentrate in either the nodes or antinodes of a standing wave, depending on whether they are hydrophilic or hydrophobic, as a result of a surface-tension effect that violates Archimedes' law of buoyancy. This clustering on waves may find practical application in particle separation and provides insight into the patchy distribution on water of, for example, plastic litter or oil slicks.

According to Archimedes' law, the mass of liquid displaced by an object is equal to the mass of that object. Small hydrophilic particles violate this law because capillarity (surface tension) pulls them deeper into the water, so the mass of the displaced liquid exceeds the particles' mass; small hydrophobic particles violate it because their mass is greater than that of the liquid they displace. Therefore when a hydrophilic/hydrophobic particle lies on a static, inclined liquid surface, there is an upwards/downwards force that is proportional to the surface slope: this can be demonstrated with hydrophilic and hydrophobic particles, which respectively climb up and slide down the meniscus (results not shown).

Standing wave patterns are characterized by certain points that undergo no vertical displacement (nodes). Fluid moves horizontally around the nodes, and midway between them are antinodes, where fluid moves purely vertically. Points on the fluid surface between a node and antinode move along inclined lines. Objects floating on such a wave should simply oscillate with the fluid, but an analysis of the interplay between gravity and capillarity shows that a net force acts on small particles floating between nodes and antinodes on a standing wave on a horizontal water surface (see supplementary information).

Let us compare the forces acting on a small particle in its high and low positions during the wave period (for calculations, see supplementary information). The first contribution to the net force is due to the fact that a particle placed between a node and antinode moves along a surface that is steeper nearer the node. In one half of the cycle, when the fluid surface is below the horizontal, the force acting on a particle is larger than in the other half of the cycle, when the surface is above the horizontal. As a result,

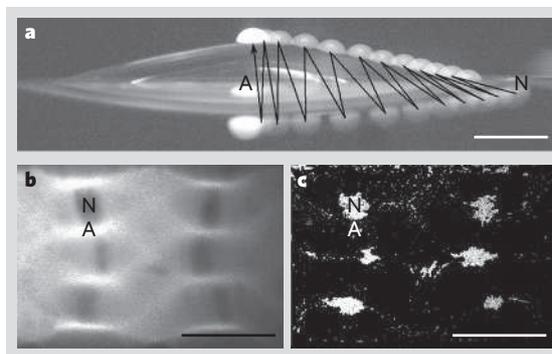


Figure 1 | Floaters in a standing wave. **a**, Stroboscopic picture (side view) of the drift of a hydrophobic teflon ball towards the point of maximum vertical displacement (antinode, A). Arrow shows the direction of the motion, which starts at the point of zero displacement (node, N). The line segments connect the centres of the ball positions at successive half-periods of the wave. **b**, **c**, Plan views of a standing wave with a shadowgraph (**b**), and showing hydrophilic particles clustering at its nodes (**c**). Scale bars, 5 mm.

there is a net force that pushes a hydrophobic particle towards the antinode, and a hydrophilic particle towards the node.

The second contribution to the force asymmetry is due to the vertical displacement of the floater. Because of inertia, the motion of a 'heavy' hydrophobic particle is retarded, whereas that of a 'light' hydrophilic particle is advanced relative to the motion of the fluid surface (as long as the wave frequency is less than the frequency of free particle oscillations — which is always the case when the wavelength is much larger than the particle size). The acceleration of the fluid surface is downwards when the fluid surface is above the horizontal, and upwards when it is below it. As a result, a hydrophobic particle is submerged to a greater depth at the lower position. Vertical displacement of a floater from its equilibrium position relative to the fluid surface produces an extra (restoring) force. This force pushes a hydrophobic particle up from its low position (and down from its high position), so that its horizontal component is directed towards an antinode. Conversely, a hydrophilic particle is submerged to a greater depth when in its higher position on the surface and the net force is towards a node.

Both these mechanisms are inertial (due to mass mismatch) and produce net forces in the same direction. The force is proportional to the square of the wave amplitude and so is a nonlinear effect.

We generated a standing wave by vertically oscillating a container¹ (see supplementary information for details of the experimental set-up). Floating hydrophobic particles attract each other, so we avoided clustering unrelated to waves by using a single hydrophobic teflon ball (density, 2.2 g cm^{-3} ; diameter, 1.6 mm). Figure 1a shows the motion of the ball, lit stroboscopically with twice the frequency of the standing wave (12.750 hertz). The stroboscope phase was adjusted to visualize only the instants of the maximal and minimal elevation of the water surface. The time taken to pass from a node to an antinode varies from 2 to 20 s, depending on the wave amplitude.

To observe the opposite direction of drift, and to study smaller particles, we used a suspension of hydrophilic hollow glass spheres of average size 30 micrometres and density 0.6 g cm^{-3} . These particles

submerge almost fully and readily form homogeneous suspensions in the absence of waves. The cell was illuminated from below and the light was recorded by two cameras synchronized with the shaker oscillations. Figure 1b shows a shadowgraph image from a camera that receives light passed straight upwards so that the white lines correspond to the wave antinodes and the black spots are shadows from the particles. Figure 1c shows an image of the same area taken by a camera that is placed to receive only light scattered by the particles so that the white spots represent particle clusters. The hydrophilic particles are clearly clustered in the nodes of the standing wave, as predicted by our calculations.

Particles on fluid surfaces can be compared with clustering phenomena such as Chladni patterns, in which sand on a vibrating elastic solid forms nodal patterns^{2,3}. Separation can also occur in such patterns (coarse grains to nodes, fine powder to antinodes), although this is a collective phenomenon^{4,5} distinct from our single-particle effect. Recall also that dust gathers at the nodal points of velocity in a standing acoustic wave⁶ (in Kundt's tube) owing to the radiation pressure gradient⁷. However, for waves in fluids, pressure is constant along the surface, so the phenomenon we describe here is different.

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BIODIVERSITY

Disease threat to European fish

The deliberate introduction of new species can have unexpected negative consequences^{1,2} and we show here how a recently introduced fish, the invasive Asian cyprinid *Pseudorasbora parva*, is causing increased mortality and totally inhibiting spawning in an already endangered native fish, the European cyprinid *Leucaspis delineatus*. This threat is caused by an infectious pathogen, a rosette-like intracellular eukaryotic parasite that is a deadly, non-specific agent. It is probably carried by healthy Asian fish, and could decrease fish biodiversity in Europe, as well as having implications for commercial aquaculture.

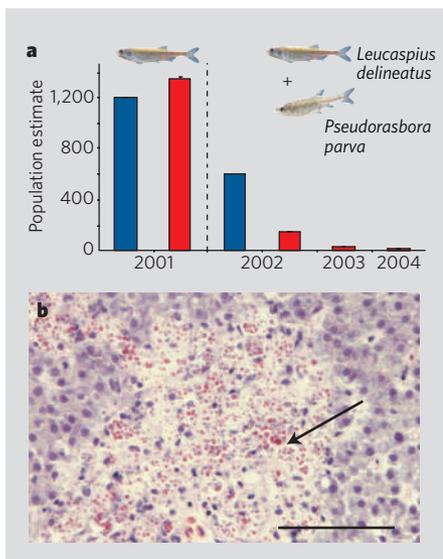


Figure 1 | Decline of *Leucaspis delineatus* population in a large natural pond after the introduction of *Pseudorasbora parva* and its associated pathogen, *Sphaerothecum destruens*. **a**, The exact maximum likelihood estimates (red bars, showing s.e.m.) for *L. delineatus* populations in the autumn are shown for four years. Starting populations in April of 2001 and of 2002 are shown as blue bars: these represent 1,200 *L. delineatus* in 2001, and 600 *L. delineatus* present in a mixed population with 600 *P. parva* introduced in 2002. **b**, High-power light micrograph of a section of a *L. delineatus* liver. There is a focus of phagocytic cells (arrow) containing conspicuous eosinophilic rosette-like agents (pink). (Slide stained with haematoxylin and eosin; scale bar, 50 micrometres.)

The sunbleak, *L. delineatus*, is the only representative of its genus and the only nest-guarding fish among European cyprinids. Once widespread in Europe, in the past 40 years it has inexplicably declined³ and is now on the European list of threatened freshwater fishes³. By contrast, since its introduction in 1960 into Romanian ponds near the River Danube, the Asian topmouth gudgeon, *P. parva*, has spread rapidly throughout Europe⁴ and has locally coincided with *L. delineatus* extinction^{5,6}.

In laboratory experiments (for methods, see supplementary information), we found that the holding water of *P. parva* acted as an absolute inhibitor of spawning for *L. delineatus* (no eggs produced in *P. parva* water compared with 1,596 ± 840 in control, clean water), and caused a large increase in fish mortality (69 ± 3% deaths in the treatment group, compared with 16 ± 2% ; $P < 0.05$, Mann-Whitney *U*-test; 4 experiments). These results were confirmed in a large natural outdoor pond, where *L. delineatus* populations declined by 96% over three spawning seasons (2002–04; Fig. 1a) after being mixed with *P. parva*, despite an increase of 13% in the year before *P. parva* arrived (2001; Fig. 1a). Spawning was totally inhibited in *L. delineatus* after *P. parva* was introduced.

We found that the decline in *L. delineatus* (caused by total inhibition of spawning, loss of body condition, and death) that resulted from sharing water with *P. parva* was caused by an infectious organism. Histological findings from moribund *L. delineatus* indicated extensive infection of visceral organs, including the reproductive tissues, with an obligate intracellular eukaryotic pathogen (Fig. 1b; see also supplementary information) similar to the lethal rosette agent *Sphaerothecum destruens*⁷ that infects Chinook salmon, *Oncorhynchus tshawytscha*, and Atlantic salmon, *Salmo salar*.

The presence of this pathogen in *L. delineatus* that had been exposed to holding water from *P. parva*, and its absence in the source population and in the control group ($n=20$), was confirmed by polymerase chain reaction amplification of its DNA using primers specific to a small segment of the ribosomal DNA of *S. destruens*. The prevalence of the rosette-

like agent in moribund or dead *L. delineatus* was 67% ($n=12$). The parasite was also detected in subclinical fish in the treatment group, but at a lower prevalence (28%; $n=32$). This level of infection is consistent with that reported in tissues of salmon exposed to *S. destruens*⁸.

Preliminary examination indicates that other cyprinids, such as the fathead minnow *Pimephales promelas*, are also susceptible to this pathogen, which causes effects identical to those in *L. delineatus* (prevalence, 20%; $n=5$). All *P. parva* specimens ($n=10$) tested for the rosette-like agent were negative: however, this is to be expected, given that pathogen concentrations in healthy carrier fish are very low and difficult to detect using conventional diagnostic tests⁹. Cohabitation studies are a recognized method for detecting carrier states for different fish pathogens^{9,10} and, as our results illustrate, they are currently the most reliable way to detect a healthy carrier.

Our results have three important implications. First, the most invasive fish species in Europe⁴ is a healthy host for a deadly, non-specific pathogen that could threaten aquaculture trade, including that of salmonids. Second, it is difficult to identify fish populations that are carriers of pathogens. Third, this pathogen could pose a threat to the conservation of European fish diversity.

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