5. R. F. Heming, *Geol. Soc. Am. Bull.* **85**, 1253 (1974).
6. K. Aki and W. H. K. Lee, *J. Geophys. Res.* **81**, 4381 (1976).
7. E. B. Bailey and C. T. Clough, *Mem. Geol. Surv. Scotl.* (1924).
8. J. E. Richey and H. H. Thomas, *ibid.* (1930).
9. E. M. Anderson, *Proc. R. Soc. Edinburgh* **56**, 128 (1936).
10. D. L. Reynolds, *Verh. K. Ned. Geol. Mijnboukd. Genoot.* **16**, 355 (1956).
11. G. P. L. Walker, *J. Geophys. Res.* **89**, 8407 (1984).
12. P. W. Lipman, *ibid.*, p. 8801.
13. W. J. Phillips, *Tectonophysics* **24**, 69 (1974).
14. J. Mori, *Int. Volcanol. Congr. N.Z.* (abstr.) (1986), p. 263.
15. T. H. Druitt and R. J. S. Sparks, *Nature (London)* **310**, 679 (1984).
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Sensory Tuning of Lateral Line Receptors in Antarctic Fish to the Movements of Planktonic Prey

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The suitability of the lateral line system of fish and aquatic amphibia for the detection of planktonic prey was examined in the antarctic fish *Pagothenia borchgrevinki* (family Nototheniidae). The best responses of primary afferent lateral line neurons to waterborne vibrations were recorded at frequencies within the range of those produced by swimming crustacea. Simultaneous recordings from a swimming zooplankter held close to the fish and from primary afferent neurons provided direct confirmation that swimming movements of crustaceans are a potent natural stimulus of the lateral line system.

THE LATERAL LINE IS AN INTERESTING and varied sensory system in fish and aquatic amphibia. The receptors of the lateral line respond to water movements (*1*), and the system is used in schooling (*2*), detection of stationary objects (*3, 4*), and detection of prey (*5–7*). However, in only a few cases can the properties of the natural stimuli be directly compared with the physiology of lateral line receptors. In this report we examine the suitability of this sensory system for the detection of planktonic prey by comparing the functional properties of the anterior lateral line system in *Pagothenia borchgrevinki* (family Nototheniidae) with the nature of the vibrations produced by the crustaceans on which it feeds. *Pagothenia borchgrevinki* is an antarctic teleost that must survive long periods of darkness during the polar winter when nonvisual systems would offer an advantage for feeding. The anterior lateral line system consists of six short dermal canals on each side of the head, opening to the outside through a series of 2 to 12 pores (Fig. 1). Vibration-sensitive neuromasts lie within the canals, one between each pair of pores.

Pagothenia borchgrevinki and zooplankton were obtained from beneath the sea ice in McMurdo Sound, Antarctica (water temperature, −1.9°C). Fish were suspended in an aquarium by a cloth sling located behind the operculum, and the gills were irrigated continuously with −1.0° to −1.5°C seawater. Water level in the tank was adjusted to uncover the dorsal surface of the head, allowing us to make a small hole in the cranium under local anesthetic to expose the root of the anterior lateral line nerve. A vibrating sphere (4.5 mm in diameter, with a movement amplitude of 0.35 mm and a flat frequency response in the range of 1 to 90 Hz) was positioned in the water near the head of the fish while the activity of single sensory neurons was recorded from the root of the anterior lateral line nerve with glass micropipettes. Each unit responded maximally to vibration within a few millimeters of either of a contiguous pair of pores, producing one or more spikes per cycle in a relatively constant phase relation to the stimulating sine wave. When the probe was shifted to the second pore, the phase of spikes shifted by 180° after passing through a null point; in this way each unit could be localized to a particular neuromast. The best responses were obtained with the probe in the immediate vicinity of a pore, and responses decreased as the probe was moved away from the pore, becoming barely discernible at distances of 20 to 25 mm. Most records were made from units of the mandibular and preopercular canals, which would be least subject to interference or reflections from the air-water interface.

Single units were stimulated for 30 seconds at each of a number of frequencies between 10 and 100 Hz. At low frequencies (10 to 20 Hz), units fired one to three spikes per cycle, weakly phase-locked to the stimulus cycle. At intermediate frequencies (30 to 40 Hz) the units typically fired one spike per cycle and were strongly phase-locked. At high frequencies (50 to 100 Hz), spikes were still phase-locked but occurred only every second or third stimulus cycle. We quantified the responses by determining the amplitude of spike latency histograms constructed over equal numbers of stimulus cycles for each stimulus frequency and by scaling each response as a proportion of the maximum response for the given unit. Most units responded maximally to frequencies of

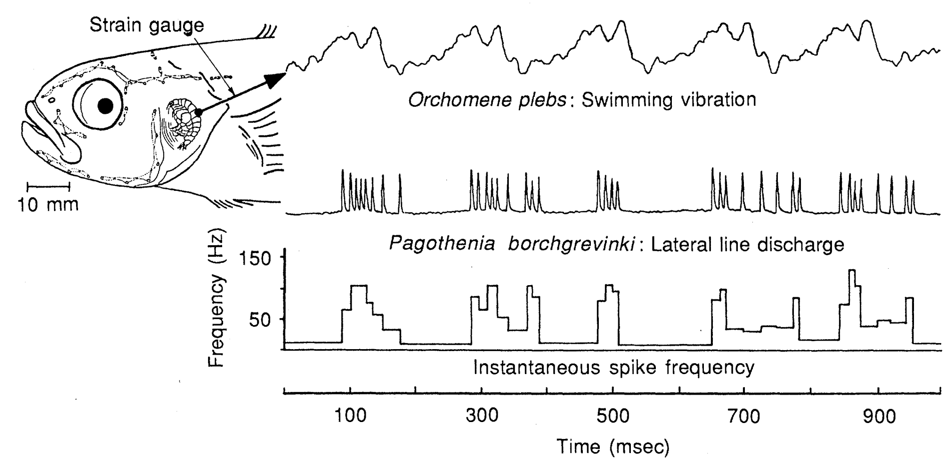

Fig. 1. Simultaneous records of the swimming vibration of an amphipod, the spike discharge of a single lateral line afferent axon (distorted in wave form owing to digitization), and its associated instantaneous spike frequency. The neuromast had previously been identified as lying between the fifth and sixth preopercular pores. The vibration record is part of the same sequence used to derive the *Orchomene plebs* power spectrum in Fig. 2B.

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40 Hz, with the responses falling off rapidly below 20 Hz, and more gradually above 50 Hz. A mean tuning curve for 13 primary afferents is shown in Fig. 2A.

Examinations of gut contents (*8, 9*) indicated that *P. borchgrevinki* feeds selectively on larger zooplankton in the upper water column. Recordings were made of vibrations produced during swimming by three crustacean species found in the diet of *P. borchgrevinki: Orchomene plebs* (Amphipoda), *Euphausia crystallorophias* (Euphausiacea), and *Euchaeta antarctica* (Calanoida). Swimming records (made by attaching the animals to a force transducer) were processed by a spectrum analyzer. They exhibited distinct low-frequency peaks at 3 to 6 Hz attributable to the basic rate of power strokes, several harmonics of the base frequency, and strong peaks between 30 and 40 Hz (Fig. 2B). The basic cycle of power and recovery stroke and the higher frequency components of the signal are evident in the swimming vibration record shown in Fig. 1. Nonswimming controls produced low-amplitude, low-frequency power spectra attributable to ventilatory movements, with a peak near 50 Hz due to electrical generator noise (*10*).

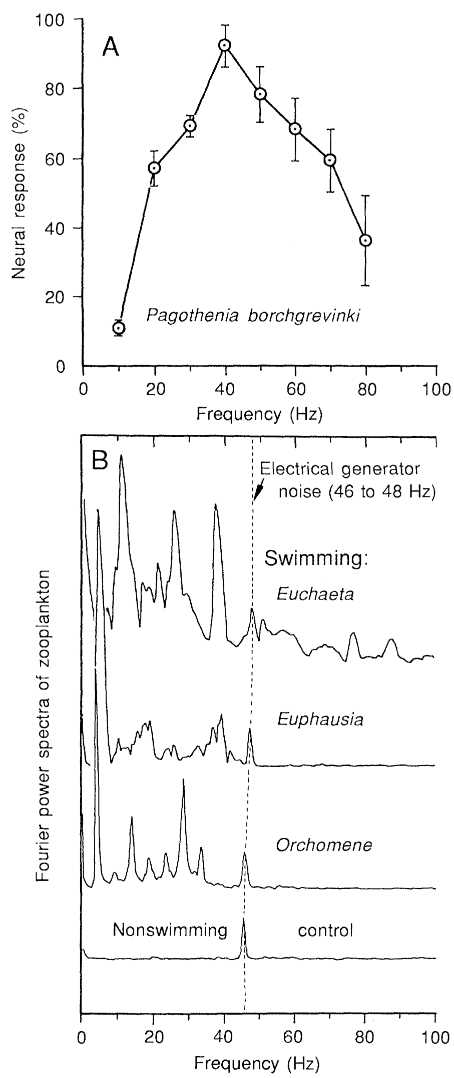

Fig. 2. (**A**) Frequency response characteristics of lateral line afferent fibers. Mean relative responses have been calculated for each vibration frequency for 13 fibers. Error bars indicate standard deviation. (**B**) Power spectra of strain gauge output attached to a swimming zooplankter (plotted with a linear vertical scale). Each spectrum was derived from swimming records consisting of 5 to 30 power stroke cycles.

The correspondence between the frequency response characteristics of the anterior lateral line afferents and the power spectra of the swimming movements of their prey establishes the suitability of the anterior lateral line system for prey detection in *P. borchgrevinki.* We obtained direct confirmation of this relation by suspending an amphipod near the head of a fish while recording the activity of neurons from lateral line afferents (Fig. 1). Simultaneous strain gauge and nerve recordings showed bursts of nerve spikes with each cycle of power stroke and recovery, indicating that vibration produced by the swimming crustacean is a potent natural stimulus of the anterior lateral line system of the antarctic fish, which may be important in the close-range coordination of feeding.

REFERENCES AND NOTES

1. O. Sand, in *Hearing and Sound Communication in Fishes*, W. N. Tavolga, A. N. Popper, R. R. Fay, Eds. (Springer-Verlag, Berlin, 1981), pp. 459–480.
2. B. L. Partridge and T. J. Pitcher, *J. Comp. Physiol.* **135**, 315 (1980).
3. C. von Campenhausen, I. Riess, R. Weissert, *ibid.* **143**, 369 (1981).
4. T. Teyke, *ibid.* **157**, 837 (1985).
5. H. Bleckmann, *ibid.* **140**, 163 (1980).
6. J. C. Montgomery and A. J. Saunders, *Proc. R. Soc. London* **224**, 197 (1985).
7. A. J. Saunders and J. C. Montgomery, *ibid.*, p. 209.
8. J. T. Eastman and A. L. DeVries, *Polar Biol.* **4**, 45 (1985).
9. J. M. Cargill and J. C. Montgomery, *N.Z. Antarct. Rec.*, 7 (No. 1), 17 (1986).
10. Force transducer records included electrical noise from the portable generator used to power the recording apparatus. Loading of the generator caused it to run slightly slower than its rated frequency of 50 Hz.
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Disruption of the Mauna Loa Magma System by the 1868 Hawaiian Earthquake: Geochemical Evidence

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To test whether a catastrophic earthquake could affect an active magma system, mean abundances (adjusted for "olivine control") of titanium, potassium, phosphorus, strontium, zirconium, and niobium of historic lavas erupted from Mauna Loa Volcano, Hawaii, after 1868 were analyzed and were found to decrease sharply relative to lavas erupted before 1868. This abrupt change in lava chemistry, accompanied by a halved lava-production rate for Mauna Loa after 1877, is interpreted to reflect the disruptive effects of a magnitude 7.5 earthquake in 1868. This interpretation represents a documentable case of changes in magmatic chemical variations initiated or accelerated by a major tectonic event.

IGNEOUS PETROLOGISTS TYPICALLY ANalyze and interpret chemical variations of volcanic rocks in terms of physicochemical processes intrinsic to a given magmatic system. Most investigators assume, implicitly or explicitly, that processes producing chemical changes operate gradually during the lifetime of that system. We present evidence that a catastrophic event, the great 1868 earthquake, may have disrupted the magma system at Mauna Loa Volcano, Hawaii, and affected the chemistry of its lavas for decades thereafter.

Mauna Loa (Fig. 1), the world's largest active basaltic volcano, last erupted in March and April 1984 (*1*). Earlier petrologic studies of Mauna Loa tholeiitic basalt (*2, 3*) showed that nearly all of the major-element variation can be accounted for by the addition or subtraction of olivine [called "olivine control" by Powers (*2*)]. A few volumetrically small tholeiites are more evolved as a result of differentiation involving pyroxene and plagioclase in addition to olivine (*3, 4*). A study of 114 samples of historic Mauna

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