pose, on the basis of both selective and physiological considerations, that evolution among heliconiine butterflies of the sensory, structural, and behavioral prerequisites for pollen collecting (*9*) might have quite readily led to the *Heliconius* pattern of living to a ripe old age (*19*) while maintaining fully functional "immortal" ovaries.

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1. V. B. Wiggelsworth, *The Principles of Insect Physiology* (Chapman and Hall, London, ed. 7, 1972). Adult Lepidoptera depend on liquid food, and the few species tested lack gut proteases: this lack is related to their predominantly carbohydrate diet from nectar or fruit. Some moths have neither functional mouthparts nor gut enzymes.
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3. M. J. Norris, *Proc. Zool. Soc. London* **1934**, 333 (1934).
4. V. M. Stern and R. F. Smith, *Hilgardia* **29**, 411 (1960).
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8. M. J. Norris. *Proc. Zool. Soc. London* **1932**, 595 (1932).
9. L. E. Gilbert, *Proc. Natl. Acad. Sci. U.S.A.* **69**, 1403 (1972). *Heliconius* adults collect pollen from blossoms of the cucurbit vines *Anguria* and *Gurania*, which bloom year-round in tropical rain forests. They then mix the pollen with liquid (probably nectar), inducing it to pregerminate and release amino acids into solution, which can then be ingested.
10. P. R. Ehrlich and L. E. Gilbert, *Biotropica* **5**, 69 (1973).
11. Unlike most Lepidoptera, *Heliconius* feeds and reproduces well in greenhouses, and *Dryas* was chosen for comparison because it is similarly adaptable. However, *Eueides*, another heliconiine that does not feed on pollen, would be a more typical lepidopteran for comparison in that it lays more eggs than *Dryas* in a shorter lifespan.
12. R. C. King, *Ovarian Development in* Drosophila melanogaster (Academic Press, New York, 1970).
13. Nectars exploited by butterflies contain some amino acids [W. B. Watt, P. C. Hoch, S. G. Mills, *Oecologia (Berlin)* **14**, 353 (1974); H. G. Baker and I. Baker, in *Coevolution of Animals and Plants*, L. E. Gilbert and P. H. Raven, Eds. (Univ. of Texas Press, Austin, 1975), p. 100] and sucrose solution may be an inadequate substitute. However, so far we have noticed no significant difference in longevity or fecundity between *Dryas* reared with sucrose solution alone and those reared with continual access to *Anguria* or *Lantana* nectar.
14. R. C. King, R. G. Burnett, N. A. Staley, *Growth* **21**, 230 (1957).
15. Mating normally occurs during emergence in *H. charitonius*, and during the first few days of adult life in *Dryas*. Unmated *Heliconius* lay many fewer eggs than mated females, but whether unmated *Dryas* will oviposit is unknown.
16. Dissections both early and late in the day reveal that *H. charitonius* normally lay all chorionated eggs each day, unless oviposition is inhibited by overcast or cold weather or lack of oviposition sites. If adverse conditions persist for more than several days, resorption begins mainly in oocytes undergoing vitellogenesis and also occurs in a few stored ovulated eggs (*17*).
17. Egg resorption in insects is reviewed by W. J. Bell and M. K. Bohm [*Biol. Rev.* **50**, 373 (1975)].
18. Means vary among *H. charitonius* females from 9 to 18 eggs per day, in direct proportion to adult size (forewing length). Slightly lower rates characterize other *Heliconius*, as for example: three to five per day in *H. erato*, five to seven in *H. ethilla* (*10*), eight to 15 in *H. hecale*, but among species they are not necessarily correlated with average adult size. We have not yet studied oviposition in *Dryas* of variable size.
19. The cause of death in *Heliconius* in nature is not known. Many greenhouse butterflies are killed by spiders. Some older *Heliconius* fail to process pollen properly, although in general the ability to collect pollen increases with age. In nature, their unpalatability probably eliminates vertebrate predation as a source of mortality [L. P. Brower, J. V. Z. Brower, C. T. Collins, *Zoologica (N.Y.)* **48**, 65 (1963); W. W. Benson, *Am. Nat.* **105**, 213 (1971)]. Older individuals have worn wings (*10*) and thinner cuticles, both involving nonrenewable tissues, and may be more susceptible to both invertebrate predation and various forms of lethal damage.
20. L. M. Cook, E. W. Thomason, A. M. Young, *Anim. Ecol.* **45**, 851 (1976).
21. In all *Heliconius* thus far studied, pollen is not essential for egg formation although the onset of oviposition appears to be delayed at least 1 day in *H. charitonius* without pollen (Fig. 1b). *Heliconius charitonius* that regularly collect more pollen do not necessarily lay more eggs, and our data are inadequate to determine whether they live longer. However, egg production in this species increases up to approximately that predicted on the basis of forewing length (*18*) in pollen-deprived females that subsequently are given and collect pollen. Experiments performed earlier by Gilbert (*9*) show that in *H. ethilla* and *H. erato*, both of which encounter pollen more dependably in their natural habitats (deep rain forests), either pollen or added dietary amino acids cause an increase in daily egg production.
22. M. L. Pan, W. J. Bell, W. H. Telfer, *Science* **165**, 393 (1969); W. W. Doane, in *Developmental Systems: Insects*, S. J. Counce and C. H. Waddington, Eds. (Academic Press, New York, 1973), vol. 2.
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24. Divisions would include both those of stem-line oogonia (which are well defined in Diptera but have not been identified with certainty in any Lepidoptera) giving rise to definitive oogonia, and the three subsequent mitoses with incomplete cytokinesis generating each eight-celled oocyte–nurse cell complex [(*12*); also W. H. Telfer, *Adv. Insect Physiol.* **11**, 223 (1975)].
25. Other heliconiines that do not feed on pollen include *Agraulis vanillae* with 90 to 100 oocytes per ovariole at emergence and *Eueides isabella* with 70 to 80. This number may in fact be correlated predictably with the quality of normal adult nutrition, at least among butterflies of about the same size as *Heliconius*. All *Heliconius* species examined emerge with fewer than 40 oocytes per ovariole. Furthermore, in *Pteronymia*, an ithomiine that feeds on nitrogenous compounds in bird droppings and lives up to 4 months in nature (*9*), only 30 oocytes are initially present in each ovariole. Most butterflies emerge with 45 to 100 or more oocytes per ovariole (*5, 6, 26*).
26. H. Dunlap-Pianka, unpublished observations.
27. M. L. Pan and G. R. Wyatt, *Dev. Biol.* **54**, 127 (1976); K. Endo, *Dev. Growth Differ.* **11**, 297 (1970).
28. Regardless of adult size or age, the sum of eggs laid plus those remaining in the ovary at dissection is remarkably consistent among *Dryas* females, ranging from 450 to 500 eggs, which is very close to the average number of oocytes at emergence (480).
29. Oogonial mitosis in young females of *Dryas* and other species (*26*) may function to replace resorbed eggs (*17*). Mitosis may also continue in some species if adults obtain optimal nutrition from certain nectars (*13, 35*), causing egg production to exceed the original number of potential oocytes.
30. *Drosophila* females deprived of essential amino acids show similar ovarian changes [J. H. Sang and R. C. King, *J. Exp. Biol.* **38**, 793 (1961)].
31. Hormones can control mitosis [R. Turkington, in *Developmental Aspects of the Cell Cycle*, I. Cameron *et al.*, Eds. (Academic Press, New York, 1971)], and the control of mitosis in imaginal disks by hormones and vitellogenin has been proposed [W. J. Gehring and R. Nöthiger, in *Developmental Systems: Insects*, S. J. Counce and C. H. Waddington, Eds. (Academic Press, New York, 1973), vol. 2, pp. 260–261]. The regulation of vitellogenin synthesis or uptake (or both) by juvenile hormone in Lepidoptera and other insects is well established [(*22, 27*); P. Sroka and L. I. Gilbert, *J. Insect Physiol.* **17**, 2409 (1971); M. M. Nijhout and L. M. Riddiford, *Biol. Bull. (Woods Hole, Mass.)* **146**, 377 (1974)].
32. M. Norris fed *Ephestia* albumen without causing increased fecundity or longevity, but since the moths lack gut proteases they could not utilize the protein (*1, 3*).
33. A postreproductive period has been proposed in warningly colored and distasteful moths, in which older individuals presumably educate predators to avoid kin [A. D. Blest, *Nature (London)* **197**, 1183 (1963)].
34. However, even *Heliconius* must eventually become senescent and die [(*19*); see also, for example, P. B. Medawar, *The Uniqueness of the Individual* (Methuen, London, 1957)].
35. Many Lepidoptera can exploit lower quality and less predictable nitrogen sources than pollen [for example, certain nectars (*13*), dung and rotting fruit (*9*)]. Hence in environments such as tropical rain forests that select for reproductive longevity, ovarian dynamics approaching those of *Heliconius* may be common.
36. We thank O. P. Breland and A. G. Jacobson for use of laboratory space and microscopic and photographic facilities, F. Davidson for photographic assistance, M. C. Singer for many suggestions and continuing interest in the research, and R. H. Barth, G. Freeman, and especially E. R. Pianka for critical reviews of the manuscript. C.L.B. is supported by an NSF predoctoral fellowship. This research was funded in part by NSF grant GB 4074 X-P to L.E.G.

25 January 1977

Bag Cell Control of Egg Laying in Freely Behaving *Aplysia*

Abstract. *Neuroendocrine (bag cell) control of egg laying was studied in freely behaving* Aplysia. *Surgical lesions showed that bag cells are not necessary for egg laying, although they play a crucial role in its control, and that the pleurovisceral connectives are the afferent pathway to the bag cells. Recording in vivo showed that synchronous bag cell spikes progressively invade the network, leading to prolonged repetitive firing that initiates natural egg laying.*

Since the initial discovery that the bag cells of the marine gastropod *Aplysia* have the morphological characteristics of neurosecretory cells (*1, 2*) and contain a hormone capable of inducing egg laying (*3*), there have been many electrophysiological (*2, 4–9*), biochemical (*10, 11*), and behavioral (*3, 11–13*) studies of this model neuroendocrine system. Bilateral bag cell clusters (about 400 somata each) are located around the pleurovisceral connectives at the rostral margin of the abdominal ganglion, and their neurites extend for a short distance within the connective tissue sheath, which is believed to serve as a neurohemal organ (*1*). Bag cells are normally silent in the isolated ganglion. Brief stimulation of the distal portion of either connective can trigger a synchronous bag cell afterdischarge lasting tens of minutes (*14*), which led to the hypothesis

that the connectives contain a descending orthodromic pathway (*15*). After injection of the perfusate from stimulated bag cells, most recipient animals lay eggs within 2 hours (*12, 16*). Since bag cells have action protentials of very long duration (*2, 4, 7, 17*), their synchronous spikes can be identified in extracellular records from the connectives near the abdominal ganglion (*6–8, 11*). The augmenting prepotentials recorded in the bag cell somata during stimulation (*2, 4*) are caused by progressive spike invasion from the distal neurites (*6, 7, 9*). However, it is not known if the bag cells fire when an animal lays eggs. We have studied bag cell control of egg laying by means of (i) surgical lesions and (ii) recording in intact, unrestrained *Aplysia*. We have observed that egg laying occurs, although rarely, after functional removal of the bag cells, but that normal egg laying is invariably preceded by synchronous bag cell action potentials triggered by descending neuronal input (*18*).

Aplysia brasiliana (*19*) were isolated in perforated chambers within large aquariums, and egg laying was recorded daily. For the lesion studies, 46 animals were matched on the basis of preoperative egg laying (*20*) into four groups: deganglionated (the abdominal ganglion with both clusters of bag cells and neurites was removed); double cut (both connectives were cut near the pleural ganglia); single cut (either the right or left connective was cut near the pleural ganglion); and mock operated (surgical controls in which no nerves were cut or neurons removed) (*21*). Therefore, some animals had no bag cells, whereas others had intact bag cells with bilateral or unilateral lesions of the putative afferent pathway in the connectives. There were no significant differences in postoperative egg laying between the mock operated and single cut groups. However, the double cut and deganglionated animals showed a large decrease in egg laying: only 27 percent of the deganglionated (N = 15) and 10 percent of the double cut (N = 19) animals laid eggs postoperatively. compared to 100 percent of the mock operated (N = 7) and 100 percent of the single cut (N = 5) animals (Table 1). After at least 10 days of postoperative observation, the remaining animals who did not lay eggs were injected with bag cell extract, and all laid large masses of eggs (Table 1). We conclude that bag cells are not necessary for egg laying, but that egg laying is profoundly impaired after their removal (*22*). Furthermore, cutting both connectives is as effective as total removal of the bag cells, whereas cutting only one connective has no effect. This is strong evidence that a neural input descending in at least one connective is required to activate the bag cells (*23*).

The lesion study emphasizes the importance of the bag cells, but cannot indicate the nature of the electrical activity that initiates normal egg laying. Bag cell function in the intact animal was examined directly by means of cuff electrodes implanted on a pleurovisceral connective close to the cluster of bag cell bodies. This technique allows simultaneous extracellular recording from many individual axons without their normal connections or ongoing activity being disrupted. Furthermore, the electrode can be implanted surgically to monitor normal activity of identified neural circuits in a freely behaving animal for days (*24*).

In previous neurophysiological studies, whole nerve stimulation has been used to activate the bag cells which do not fire spontaneously in isolated ganglia. Since this form of stimulation is artificial, it cannot provide direct evidence concerning the natural firing pattern of these cells. Therefore, in order to bridge the gap between previous studies of bag cell activity in isolated ganglia and our studies of natural bag cell activity, we first examined the activity of triggered bag cells in the intact animal. A prediction from previous experiments in vitro (*4, 12*) is that electrical stimulation of the connective in vivo should trigger synchronous bag cell activity and thereby initiate egg laying. To test this, we triggered bag cell activity by stimulating through the cuff electrode on the bag cell neurites; egg laying occurred within 90

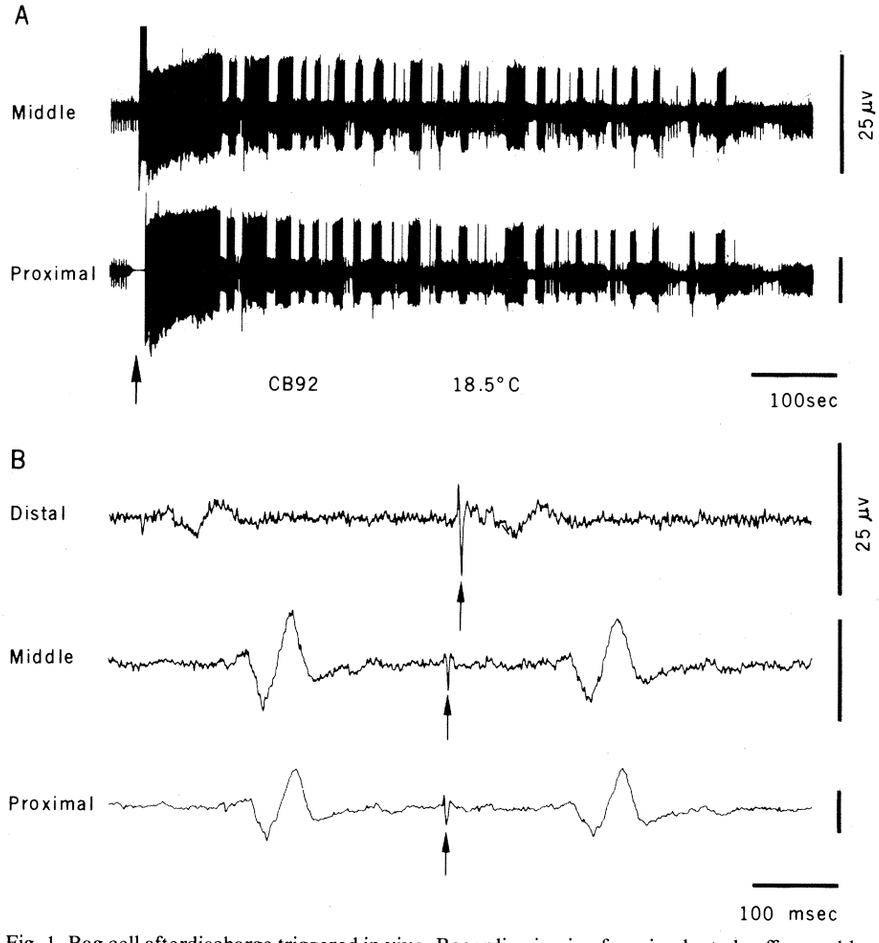

Fig. 1. Bag cell afterdischarge triggered in vivo. Recording in vivo from implanted cuff assembly with three monopolar electrodes: proximal electrode close to bag cell bodies; middle electrode 2 mm from the proximal; and distal electrode 1 cm from the middle electrode. (A) Entire (9.4 minutes) triggered afterdischarge consisting of synchronous bag cell spikes. Bag cells stimulated (0.3-msec pulses, 24 volts, 7 hertz for 5 seconds; large arrow) through the proximal electrode (proximal amplifier grounded during stimulus; artifact visible on middle electrode recording). After 1 minute of steady firing, action potentials fired in irregular bursts. Smaller amplitude signals were spontaneously active conventional spikes. The animal (*CB92*) began to lay eggs between 60 and 90 minutes after the onset of bag cell activity (total, 2 ml of eggs). (B) Individual synchronous bag cell action potentials in the same preparation recorded at higher speed. Long-duration and characteristic waveform of compound bag cell spikes are compared to conventional unitary action potential (small arrows). These waveform characteristics allow us to identify unambiguously the spontaneously occurring bag cell spikes. Bag cell spikes propagated from distal neurites toward somata, the other spike traveled in opposite direction.

minutes in four out of six animals. Triggered bag cell afterdischarges that were recorded in vivo were similar to those recorded in vitro (*7–9, 25*): slowly conducting, compound action potentials of long duration, which usually traveled from distal neurites toward the somata and decreased in frequency and amplitude during the afterdischarge (Fig. 1). This confirmed the prediction from studies in vitro and showed that we could record bag cell activity in vivo and simultaneously monitor egg-laying behavior.

What are the electrical events in the bag cells that precede natural egg laying? To answer this question, we implanted cuff electrodes in animals that laid eggs regularly. The electrical activity was continuously recorded and taped while the animals were observed every 30 minutes for egg laying (*26*). Spontaneous egg laying occurred 19 times in 12 animals: egg laying was always preceded (*27*) by repetitive bag cell activity (Fig. 2), and bag cell activity was always followed by egg laying (*28*). Spontaneous bag cell activity typically consisted of a single prolonged discharge [average duration 22.5 ± 13.0 minutes (± standard deviation), $N = 15$] (Fig. 2A1). However, four double discharges occurred separated by 2.5 to 30 minutes of silence (Fig. 2A2). Spontaneous bag cell activity (Fig. 2) was similar to triggered activity (Fig. 1) in the temporal pattern and waveforms of the compound spikes. Each discharge began with 20 to 60 seconds of regular spiking followed by irregular bursts of spikes of decreasing amplitude (Fig. 2A). One important feature of our recording is that spontaneous bag cell activity typically began with potentiating spikes originating in the distal neurites that progressively invaded closer to the somata (Fig. 2B). This indicates that this form of potentiation, which has been studied extensively in isolated ganglia subjected to electrical stimulation (*4, 6, 7, 9*), actually occurs under natural circumstances.

In conclusion, electrical activity of a population of neuroendocrine cells in *Aplysia* has been directly related to natural reproductive behavior in vivo. Although the bag cells are not absolutely necessary for egg laying, they play a critical role in the normal control of this behavior. Apparently, the pleurovisceral connectives are the only afferent pathway for activating the bag cells. Spikes initiated in the distal bag cell neurites progressively invade the entire network. This leads to repetitive synchronous action potentials which presumably cause release of a pulse of bag cell hormone.

The distinction has been made between (i) reflexive behaviors which are under control of a specific stimulus whose intensity determines the amplitude of the response and (ii) centrally commanded behaviors (or fixed action patterns) that occur spontaneously but can also be triggered by threshold amounts of some stimulus (*29*). We believe that egg laying represents a centrally commanded behavior; however, the bag cells provide the central command for egg laying by release of hormone, rather than synaptic transmitter. Now that bag cell activity in vivo can be related to spontaneous egg laying, it should be possible to determine the neuroethological factors that regulate bag cell activation under natural condi-

Table 1. Average frequency and amount of egg laying in *A. brasiliana* before and after surgery.

Surgical group	Preoperative egg laying			Postoperative egg laying			
	Animals laying eggs (%)	Total days laying eggs (%)	Egg quantity per episode (ml)*	Animals laying eggs (%)	Total days laying eggs (%)†	Egg quantity per episode (ml)†	Egg quantity after bag cell injection‡
Mock operated	100	55.7	3.9 ± 0.94	100	60.4	3.1 ± 0.6	
Single cut	100	59.8	3.1 ± 1.1	100	54.2	2.7 ± 0.76	
Double cut	100	54.2	3.3 ± 1.0	10	19.0	4.3 ± 1.9	10.2 ± 5.9
Degangli-onated	100	58.9	3.3 ± 1.2	27	16.7	8.8 ± 2.2	9.4 ± 5.2

*See (*20*). †The values are only for those animals in each group that spontaneously laid eggs. ‡Animals that did not spontaneously lay eggs within 10 to 12 days after surgery were injected with bag cell extract; only the values for these animals are shown.

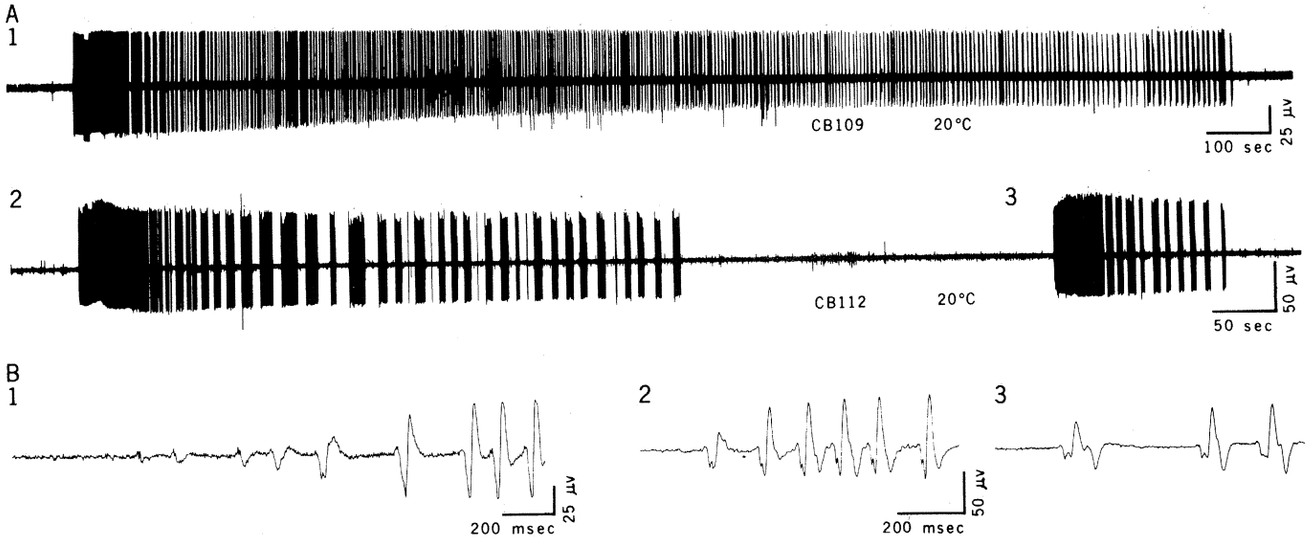

Fig 2. Spontaneous bag cell discharges in vivo. (A) Single cuff records of spontaneous bag cell activity in two animals (*CB109* and *CB112*). First animal (A1): single discharge began at 9:43 a.m., total duration 29.8 minutes; began to lay eggs (total, 2 ml) before 12:30 p.m. (*28*). Second animal (A2 and A3): double discharge began at 4:57 p.m.; began to lay eggs (total 2.5 ml) before 5:30 p.m. The first discharge (A2) was followed after 4.8 minutes of silence by a second discharge (A3). (B) Onsets of discharges shown in (A), recorded at higher speed. In each case, compound spikes potentiated rapidly as activity spread throughout the network.

tions. Furthermore, since studies in vitro have shown that bag cell hormone regulates activity of neurons in the abdominal (*5*), buccal, and pedal (*30*) ganglia, it may be possible to examine the hormonal control of neuronal circuits in vivo that mediate the different behavioral components of egg laying.

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13. F. Strumwasser, J. W. Jacklett, R. B. Alvarez, *Comp. Biochem. Physiol.* **29**, 197 (1969); W. P. Aspey and J. E. Blankenship, in preparation.
14. Spikes from bag cells within a cluster are synchronous (*2*) and it has been suggested that this synchrony is due to electrical coupling (*4*).
15. Bag cell neurites extend less than halfway up the connectives, yet electrical stimulation of the connectives near the pleural ganglia can evoke bag cell responses whereas stimulation of other nerves does not (*4*).
16. Injection of bag cell extract in the whole animal can cause eggs to appear in the small hermaphroditic duct within 1 minute. [R. E. Coggeshall, *J. Morphol.* **132**, 461 (1970)]. Some animals do not lay eggs when injected with bag cell extract, indicating that the extract is not always sufficient to trigger egg laying. This is probably because of the absence of eggs in the ovotestis of some animals (W. P. Aspey and J. E. Blankenship, unpublished observations). In addition to the peripheral effect, bag cell extract also has central effects on abdominal ganglion neurons (*5*).
17. Neuroendocrine cells generally have longer spike durations than conventional neurons. For review, see L. H. Finlayson and M. P. Osborne, *Adv. Comp. Biochem. Physiol.* **6**, 165 (1975).
18. A preliminary report of some of these findings has appeared: F. E. Dudek and H. M. Pinsker, *Soc. Neurosci. Abstr.* **6** (1976).
19. Most previous studies of egg laying in *Aplysia* have been carried out on *A. californica*. The identified neurons in the abdominal ganglion of both species have similar electrophysiological and anatomical characteristics [J. E. Blankenship and R. E. Coggeshall, *J. Neurobiol.* **7**, 383 (1976); (*8*, *9*)].
20. Egg quantity was measured as the volume of displaced seawater. For the 46 animals in this study, the average amount of eggs laid preoperatively was 3.34 ± 1.08 ml per day.
21. In the double and single cut groups, the free ends of the cut nerves were tied off. In single cut animals, there was no obvious difference between those with the left ($N = 3$) and those with the right ($N = 2$) connectives intact. Postoperative observations were conducted blind. Only animals who survived at least 4 days after surgery were included. Postoperative mortality was approximately equal for the four groups: one of seven mock operated, one of five single cut, five of 19 double cut, and two of 15 deganglionated animals died before we completed 10 days of postoperative observation.
22. The occasional egg laying in the deganglionated and double cut animals was probably the result of a peripheral mechanism triggered by the buildup of eggs in the ovotestis (F. E. Dudek, J. S. Cobbs, H. M. Pinsker, in preparation). The evidence for this hypothesis is as follows: (i) normal animals tend to lay more eggs after they miss a day or two, suggesting that eggs gradually build up in the ovotestis; (ii) the deganglionated and double cut animals who laid eggs postoperatively usually did so in large amounts (Table 1); and (iii) those deganglionated and double cut animals who failed to lay eggs spontaneously after 10 to 12 days after the operation were injected with bag cell extract and typically laid extremely large amounts of eggs (Table 1). F. Strumwasser, F. R. Schlecte, and S. Bower [*Fed. Proc. Fed. Am. Soc. Exp. Biol.* **31**, 405 (1972)] found that deganglionated animals can show normal egg-laying behavior when injected with bag cell extract.
23. Cutting both connectives near the pleural ganglion may have had some deleterious (trophic) effect on the bag cell neurites instead of, or in addition to, removing orthodromic input. However, a neurotrophic effect on bag cells would probably require several days to impair egg laying, whereas the double cut animals stopped laying eggs immediately after surgery. Other evidence (*15*) supports the hypothesis of a descending orthodromic input.
24. For recording from vertebrate nervous systems in vivo, see M. I. Phillips, Ed., *Brain Unit Activity During Behavior* (Thomas, Springfield, Ill., 1973). For recording from arthropods in vivo, see H. Aréchiga and C. A. G. Wiersma, *J. Neurobiol.* **1**, 71 (1969); J. J. Wine and F. B. Krasne, *J. Exp. Biol.* **56**, 1 (1972). For recording from mollusks in vivo see K. R. Weiss, J. Cohen, I. Kupfermann, *Brain Res.* **99**, 381 (1975); A. Gelperin and D. Forsythe, in *Simpler Networks and Behavior*, J. C. Fentress, Ed. (Sinauer, Sunderland, Mass., 1976); H. M. Pinsker, J. Cobbs, J. E. Kanz, *Fed. Proc. Fed. Am. Soc. Exp. Biol.* **35**, 769 (1976); *Soc. Neurosci. Abstr.* **6**, 353 (1976); J. Cobbs and H. M. Pinsker, *ibid.*, p. 342.
25. The intense stimulation of the connective required to trigger the bag cells (*4*) often produced side effects in the intact animal such as inking and massive contractions. Intrasomatic and extracellular studies in vitro (*8*) indicated that electrical extrasomatic stimuli to the bag cells could also initiate an afterdischarge. Although stimulus artifacts obscured the direction of spike conduction during the stimulus train, after it was terminated the spikes typically propagated from distal neurites along the ipsilateral connective toward the bag cell somata. These brief extrasomatic stimuli probably directly activated an intrinsic mechanism of the bag cells for repetitive firing. This suggests that the putative neuronal input might also trigger this intrinsic mechanism rather than driving individual bag cell spikes.
26. Animals were rejected if no spikes from conventional (non–bag cell) axons were recorded from the connective when the animal was stimulated mechanically. Several animals were monitored simultaneously, and records of bag cell activity were kept on FM tape and on a pen recorder.
27. We observed a few cases of egg laying in animals from which we had not previously recorded bag cell activity. In these animals, we stimulated the connective maximally but were unable to record bag cell activity; this indicated that our electrode was misplaced.
28. The longest latency from onset of spontaneous bag cell activity to the appearance of eggs was between 137 and 167 minutes (this animal's discharge is shown in Fig. 2A1). When behavioral observations were made at shorter intervals to get a more accurate measure, the mean latency ($N = 7$) was 29.9 ± 5.3 minutes.
29. E. R. Kandel, in *The Neurosciences, Third Study Program*, F. O. Schmitt and F. G. Worden, Eds. (MIT Press, Cambridge, Mass., 1974), p. 347.
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31. This research was supported, in part, by grants NS 11255-03 and NS 12223-01 to H.M.P. and by grant NRC A0395 to F.E.D. We thank J. Cobbs for invaluable help in the experiments; A. Gelperin, D. Forsythe, and I. Kupfermann for advice concerning the cuff electrodes; and W. Aspey, J. Blankenship, R. E. Coggeshall, W. D. Willis, Jr., and C. Taylor for criticism of an early draft of this report.

23 November 1976; revised 25 January 1977

Motion Sickness: An Evolutionary Hypothesis

Abstract. *Since the occurrence of vomiting as a response to motion is both widespread and apparently disadvantageous, it presents a problem for evolutionary theory. An hypothesis is proposed suggesting that motion sickness is triggered by difficulties which arise in the programming of movements of the eyes or head when the relations between the spatial frameworks defined by the visual, vestibular, or proprioceptive inputs are repeatedly and unpredictably perturbed. Such perturbations may be produced by certain types of motion, or by disturbances in sensory input or motor control produced by ingested toxins. The last would be the important cause in nature, the main function of the emesis being to rid the individual of ingested neurotoxins. Its occurrence in response to motion would be an accidental by-product of this system.*

Current knowledge about motion sickness has been reviewed by Money (*1*). In summarizing the explanatory problem presented by the condition, Money and Myles (*2*) described it as "an evolutionary anomaly. . . . There is no survival value in experiencing nausea, or in vomiting, when exposed to motion, and so it is surprising that the powerful central mechanism of vestibulo-gastric illness arose in many different species." Motion sickness is disabling, unpleasant, and common. The central component is vomiting and the most frequently reported accompaniments are pallor, sweating, and nausea. To those who suffer from it, it is highly disadvantageous. Why then should it occur?

Two explanations have been advanced (*1*–*3*). The first, which attributes the condition to conflict between sensory inputs, was recently restated by Reason and Brand (*3*) who argue that "situations which produce motion sickness are all