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CURRENT PROBLEMS IN RESEARCH

Nest Climate Regulation in Honey Bee Colonies

Honey bees control their domestic environment by methods based on their habit of clustering together.

James Simpson

The individual bees of a colony of honey bees cluster together in their nest position. Within the isolated microclimate of this cluster, vertical wax combs are built and the other domestic activities of the colony proceed. Clustering depends on bees attracting one another by sight, vibration, heat, and the odor of the abdominal scent glands. A minimum of about 50 bees is necessary for a cluster to form at 20°C, though smaller numbers will cluster at lower temperatures (*1*, *2*). This clustering behavior differentiates honey bees from bumble bees and social wasps, which either expose their combs to the outside environment or build some sort of protection round them.

Cluster Temperatures

Cluster temperatures in winter were measured before the end of the 18th century, but the first measurements in summer seem to have been made by Lammert in Germany in 1894 and by Gates in Washington, D.C., in 1908 (*3*). The early workers used mercury thermometers. Thermocouples are now generally used, as they are cheaper and smaller and can be used in large numbers. They can be read at a distance, so that the colony is not disturbed, and with suitable amplifying and recording apparatus they give continuous records. Thermocouples have been placed among the bees, in small glass tubes perpendicular to the combs, or in comb foundation, so that the bees build them into the combs (*4–6*).

A compact area of comb underneath the honey that normally occupies the upper and outer regions of the cluster is used for breeding—that is, for the rearing of bee larvae and their metamorphosis to adult bees. The temperature (*7*) in the middle of the brood nest in the summer is normally about 34° to 35°C, with frequent fluctuations of up to 0.5° (*3*, *8*). This is usually the hottest part of the colony (apart from the bodies of the bees themselves), though temperatures up to 39°C have been reported where combs are being built (*3*, *4*). Temperatures are 3° to 4°C lower, and less constant, in the outer regions of the brood area, and they go down to about 25°C in the broodless part of the cluster (*8*). It has been reported that the brood-nest temperature is steadiest when the cells contain eggs, that it becomes more variable as the larvae grow; and that it may fluctuate by as much as 4°C when the cells are sealed (the pupal stage) (*4*).

The brood nest gets cooler in cold weather but rarely goes below 30°C, though breeding has been recorded at temperatures down to about 25°C. The brood-nest temperature can remain within a range of 5°C while the outside temperature varies from − 40° to +40°C or more, and breeding can occur in the coldest winter weather (*5*, *8–11*).

Temperatures as low as 15°C have been recorded at the center of clusters in colonies without brood in winter, but the usual minimum is about 20°C (*8*, *12*). Temperatures as low as 4.5°C have been recorded among bees at the periphery of the cluster (*10*, *13*), but such conditions cannot last long, for inactive bees go into chill coma at temperatures below 8°C (slight acclimatization to low temperatures can occur), and, though they might then still remain attached to the cluster if undisturbed, they would die in a day or two (*14*). The usual minimum is probably not much below 9° to 10°C (*9*, *11*, *12*, *15*). In effect, the bees keep the center of their cluster at a constant temperature in summer and its periphery above the vital minimum in winter.

Temperature Regulation

The basic reason for the relatively high temperature in the middle of a cluster is that bees, like all fast-moving insects, have a high metabolic rate. An inactive bee at 35°C consumes at least 1 microliter of oxygen per minute. This, relative to body weight, is comparable to the oxygen consumption of a man doing hard manual work (*8*, *16*). The body temperature of an isolated resting bee is close to that of its environment because it is small and has a proportionately large cooling surface. When a whole colony of 10,000 to 50,000 bees are clustered together, their heat is conserved, and a substantial difference between cluster and outside temperatures is inevitable (*17*). As the metabolism of fully grown larvae is comparable with that of inactive adults, the brood also produces much heat (*8*). The metabolic rate of bees depends on their activity; a flying or fanning bee produces perhaps 100 times as much heat as a resting one (*8*, *18*).

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The body temperature of mammals is controlled by varying the peripheral blood circulation and so adjusting heat loss; by varying the amount of heat produced by muscles; and by cooling from the evaporation of sweat. There is no doubt that bees also have an active cooling system that prevents temperature from going too high, but it is not certain whether temperature is maintained in cold weather by increased heat conservation alone or whether conservation is supplemented by increased heat production.

Control by adjustment of heat loss. It may be readily seen that a bee cluster contracts when the weather is cold and expands when it is warm (Fig. 1). In winter (at temperatures below about 5° to 10°C), the cluster's edge is more sharply defined than at other seasons because the bees at the surface are chilled and so move only sluggishly and cannot leave the cluster. The bees that do leave the colony to fly on sunny but cold days, and those that attack intruders, come from warmer regions inside the cluster. Their movements raise the temperature of the cluster rapidly, and this facilitates their exit (*6, 8, 19*). Bees in winter have reserves of food (up to 40 milligrams) in their honey stomachs (*20*).

Cluster contraction conserves heat by diminishing the area of cooling surface and probably also by diminishing internal convection currents (*10, 21*). However, the cluster becomes filled with combs at its maximum summer volume, and subsequent contraction and the decline in bee population when breeding stops in the autumn leave large parts of the combs projecting in winter (Fig. 2). The heat loss from these "cooling fins" is not diminished by cluster contraction (*4*), and the bees minimize it by keeping the cluster largely on empty combs, which have a much lower conductivity than combs filled with honey (*22*).

Although cluster size and outside temperature are directly correlated, the relationship in winter is not a rigid one. This may show that the bees have a wide temperature tolerance, but any variations in the activity of the bees from nonthermal causes must contribute to the scatter of the correlation (*15*); temperatures at the center of the cluster often fluctuate sharply by as much as 5° to 8°C without any obvious relation to environmental factors (*12*). The sounds produced by a colony after a change in temperature (*23*) show that it takes some time for the bees to settle down to the new conditions.

The immediate cause of cluster contraction is probably simply that bees crowd together when they feel cold. Their thermal preferences have been investigated with a temperature "organ." Bees were put into a chamber of which the bottom was a metal bar, of uniform cross section, heated at one end and cooled at the other so that there was a temperature gradient along it. The preferred temperature region was taken to be the one where the bees came to rest. Very young bees in summer chose the temperature region of about 35°C; older bees preferred a temperature range of from 31° to 36°C. Lower temperatures were preferred in winter. Suitable acclimatization caused the bees to select the region of 28°C (*24*). Other factors also influence preference; in an observation hive where combs with brood had been put in positions away from the center of the cluster, bees were denser and the temperature was higher, usually by 3° to 4°C, over the brood than elsewhere. In contrast, temperatures at the center of the cluster were about as high without brood as with it.

Undisturbed colonies killed with hydrogen cyanide have shown that the winter cluster is divided roughly into an outer shell of closely packed bees and an inner core where the bees have room to move (*11*). It has been calculated that contraction of such a structure in cold weather to maintain a constant temperature at the periphery would increase the temperature at the center (*25*). Such an inverse relationship has sometimes been observed between temperatures at the center of the cluster and daily changes in outside temperature, but not with changes over longer periods (*8*). If a drop in outside temperature does at first produce a rise in temperature in the middle of the cluster, this rise is evidently not maintained, and some more slowly acting mechanism must operate when the low outside temperature persists. This other factor may be an increase in the density of packing of the bees in the outer regions of the cluster. If the contact between the bees' bodies increases as the cluster contracts, the thermal conductivity of the outer layer will increase (*21*) and heat will then pass through more easily, warming the outer bees and cooling the inner ones. A simple explanation of this could be that cold bees on the outside push inwards and hot bees on the inside push outwards, thus compressing the shell of bees till enough heat is transmitted to produce the observed effect. The characteristic head-inwards position of bees at the

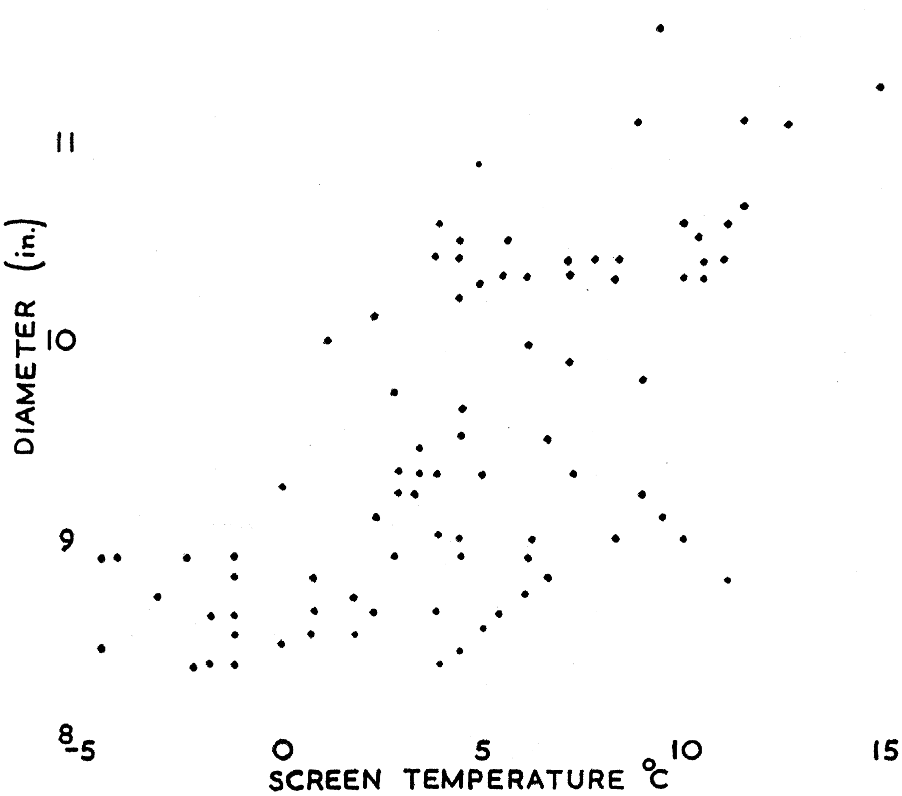

Fig. 1. Cluster diameters of a colony at different environmental temperatures (*15*).

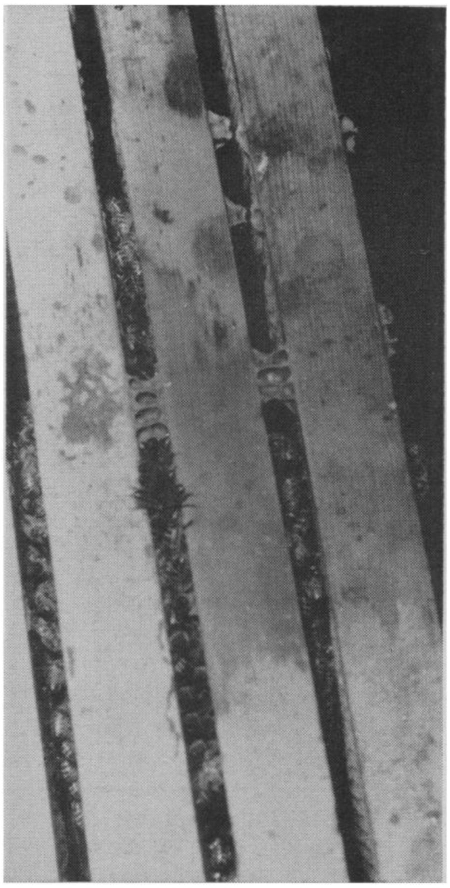

Fig. 2. A small colony of bees in winter. The cluster of bees is closely contracted and covers only a small area of the combs. The outer bees have their heads inward. (The combs are built into movable wooden frames that can be handled by the beekeeper.)

outside of a winter cluster (Fig. 2) supports the idea that they are pushing inwards.

Control by varying heat production. Whereas there is clearly some degree of temperature control through adjustment of heat loss, the evidence for control through adjustment of heat production is less satisfactory, though some people have assumed that the latter is the only method used to counteract low temperatures and have even calculated the amounts of food that colonies should consume at various outside temperatures and in hives with various measured thermal permeabilities (*3, 4, 6*).

It is now established that there is a temperature somewhere between 15° and 20°C at which inactive bees, individually exposed, have a maximum metabolic rate. At this temperature their metabolic rate is probably four to five times the rate at 35°C. At lower temperatures the metabolic rate decreases; at the temperature of the cluster surface in winter, the metabolic rate is less than it is at 35°C, and at still lower temperatures it decreases rapidly (*16*). These conclusions, based on respirometer measurements with single bees, are open to the objection that an increase in rate of respiration in cooled bees may result from their struggling to escape to find other bees to cluster with, and that no such increase would be shown by bees in a cluster. However, the respirometer results have been confirmed for the temperature region between 17° and 35°C by measurements of the food consumption and temperatures of groups of bees small enough to have much the same temperature throughout their clusters (*2*) (Figs. 3 and 4).

In winter, the temperature for maximum metabolic rate usually lies in a zone between the center and the periphery of the cluster. Whether this zone moves inwards or outwards or merely stays in the same place when outside temperatures go down, and whether there is any change in the number of bees exposed to the temperature at which metabolic rate is highest, cannot be discovered from existing temperature measurements and is probably not deducible theoretically. It would seem to be to the advantage of the colony that metabolic rate should increase only when the limit of control by heat conservation is reached—that is, at very low outside temperatures or with very small colonies—but the finding that there is a temperature at which individual bees have maximum metabolic rate does not of itself show that this is what happens. The answer can only come from experiments with whole colonies.

Evidence of inverse relationships between cluster temperatures and outside temperatures has been held to provide evidence of control through adjustment of heat production, on the unwarranted assumption that a rise in cluster-center temperature must indicate increased heat production, and vice versa. A second fallacious assumption has been that, because the center of a cluster is hotter than the periphery, the bees at the center must be producing more heat than those further out. So long as the bees in the center are producing any heat at all, they must continually lose heat to the outer bees to remain at a steady temperature, and as heat can only pass from a hotter region to a colder one, the inner bees must be hotter than the outer ones.

Movements of bees seen in the center of a colony in winter, clustered against glass, have been interpreted as special heat-producing activity to counteract low outside temperatures (*6*), but similar movements can be seen in a heated observation hive in summer, when extra heat production would not be needed. However, failure to see special heat-producing movements does not prove there is no mechanism producing additional heat, because heat could be generated by opposing muscular tensions without any visible movement except that of more frequent breathing.

Records of the amount of food consumed by colonies in winter (estimated by loss in weight) usually fail to show any definite correlation with outside temperature because other factors influence weight loss. The few records that do appear to be significant (*10*) suggest that low temperatures decrease rather than increase food consumption.

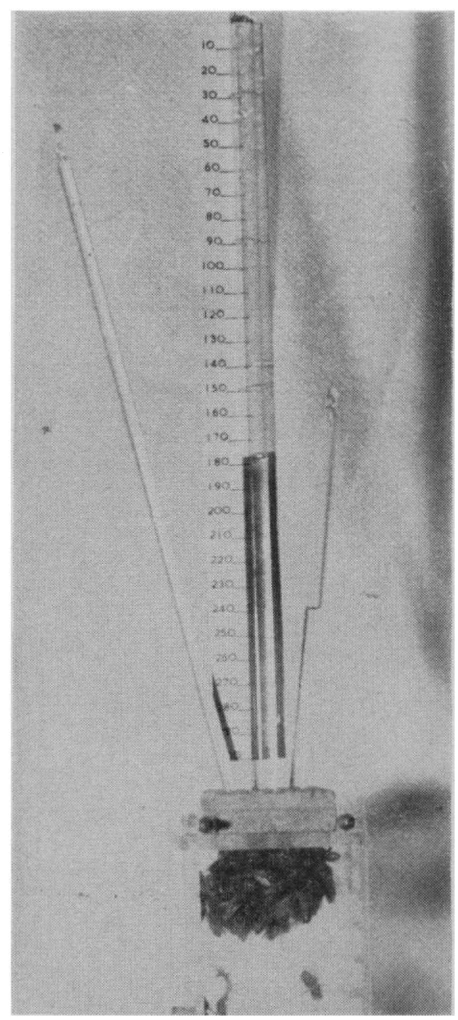

Fig. 3. A method of measuring the food consumption of a small cluster of bees (*2*). The feeder in the center contains sugar syrup; that on the right, water. The thermometer measures the temperature of the cluster. The whole apparatus is exposed to a series of environmental temperatures.

A measurement of the carbon dioxide evolved by a whole colony at different temperatures led to a similar conclusion. Comparisons of the winter weight losses of colonies in insulated hives, or in hives in bee houses or cellars, with losses of colonies in single-walled hives outside have given contradictory results. As this kind of protection from cold also diminishes temperature fluctuations, the protected colonies may eat less because they are less disturbed (*8*).

Colonies in North America, whether in insulated hives or not, seem to require at least four times as much winter food as colonies in Germany (*11, 26*), but this is probably because the strains of bee and the methods of management preferred in America produce larger colonies and much more autumn and winter brood.

The available evidence (*10, 12, 27*) seems to show that the difference between the temperature outside a hive and the temperature inside it, but outside the cluster of bees, is greatest when outside temperatures are low. If this is so, it is probably the only current evidence of increased metabolic rate at low temperatures for whole colonies.

Active Cooling

When outside temperatures approach levels necessary for domestic activity in the colony, the bees do not need to cluster to conserve heat, but they cannot spread apart indefinitely, as certain minimum densities are required for feeding the brood, building the comb, storing honey, and so on. These aggregations could cause excessively high temperatures if cluster expansion were the only means of preventing overheating. In fact, colonies have been subjected experimentally to temperatures as high as 50°C without their cluster temperatures exceeding about 38°C, so long as their cooling mechanism could function (*5, 8*).

Excessively high temperatures are prevented by rapid exchange of air between the cluster and the outside, by chains of bees fanning with their wings, and by watery material evaporated on the bees' mouth parts and on comb surfaces (*5, 28, 29*). Nectar to be concentrated is exposed in the same way (*8*). Water evaporation is a response to high temperature and not to low relative humidity. Water for cooling is collected by foraging bees. A high sugar concentration in the food that is constantly being passed from bee to bee in the colony stimulates the collection of water. Thus, collection of water is induced by water shortage resulting from evaporation and not directly by high temperature. When a colony is supplied with dyed water, the material exposed for evaporation is colored, so it must come, at least in part, from the bees' honey stomachs. Water in the honey stomach probably always contains some sugar, as bees cannot live long without food. There is no clear demarcation between water collection and evaporation and nectar collection and concentration. Colonies that are overheated or have been unable to collect water for several days prefer dilute to concentrated nectar (*29*). Colonies given colored water produce colored honey.

Fanning to cool or ventilate the cluster (ventilation fanning) must be distinguished from the kind of fanning in which the abdominal scent glands are open, which is part of the mechanism of colony cohesion and orientation (communicative fanning). German writers call the former *fächeln* and the latter *sterzeln*. Rather surprisingly, it is always communicative fanning that is induced by blowing smoke into a colony.

In ventilation fanning, *Apis mellifera* usually drives air away from the cluster; *A. cerana* drives air towards it (*30*). In an observation hive, chains of bees all fanning in the same direction seem to form only outside the cluster. Bees fanning inside the cluster seem to do so more or less at random; sometimes two bees can be seen fanning head to head in opposite directions. Presumably such bees accelerate the escape of gases produced in the cluster simply by dispersing local accumulations.

Ventilation fanning has been induced experimentally by overheating colonies (*5, 8, 28*). It is also much in evidence when nectar is being concentrated, when the stimulus is probably high humidity. High temperature induces exposure of water to evaporation, so it may cause fanning indirectly.

Cluster Humidity

Humidity in a hive but outside the cluster of bees can be measured with an ordinary hair hygrograph (*8*) or psychrometer (*4*), but within the cluster, particularly in winter, it is measurable

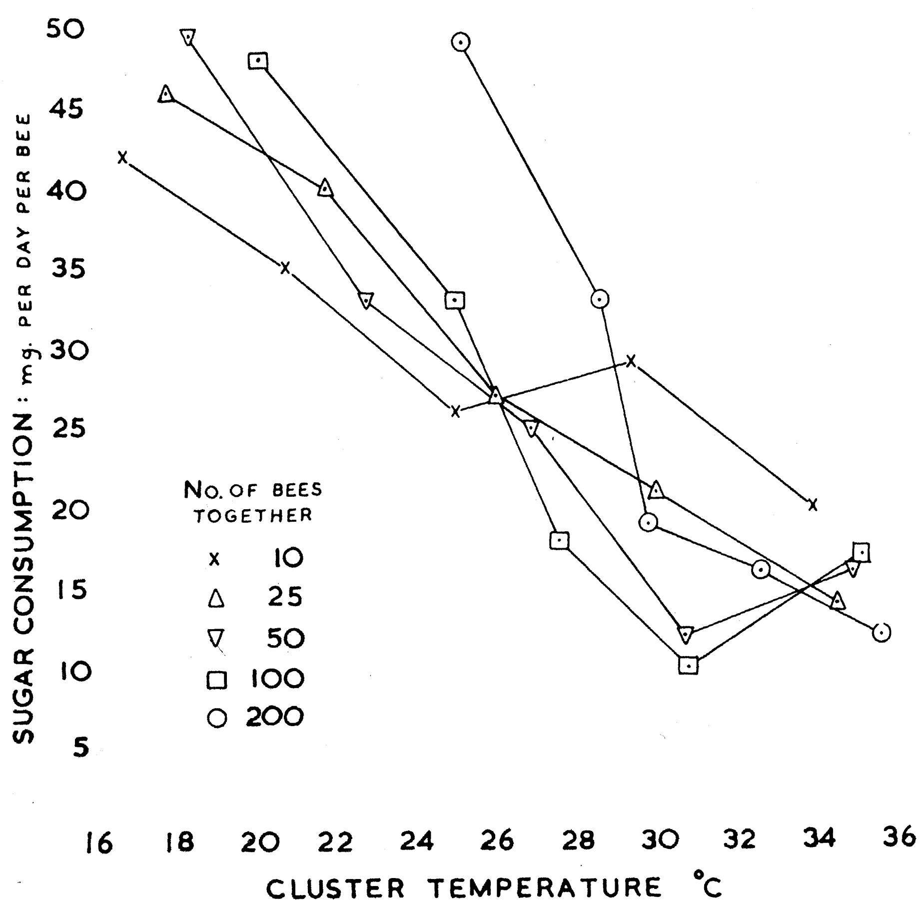

Fig. 4. Food consumption of bees at different temperatures, as measured by the method shown in Fig. 3.

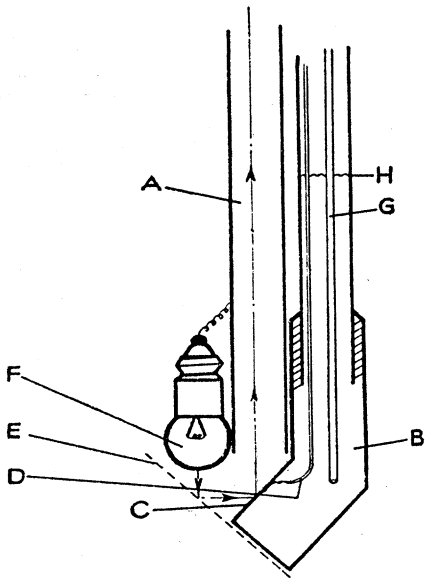

Fig. 5. Apparatus for measuring the dew point in a cluster of bees (*9*). Only a portion of the glass tubes is shown; their total length is about 23 centimeters. *A*, viewing tube; *B*, metal thimble cemented to glass tube with Polythene; *D*, thermocouple soldered to the back of a metal mirror *C*; *E*, part of a perforated zinc screen to exclude bees and provide the image seen in the mirror when no dew is present; *F*, light bulb; *G*, tube for air to vaporize ether; *H*, ether level before evaporation. [Actual size]

only with apparatus that takes up little space and gives an accurate reading with a small volume of air. A microdewpoint apparatus with the mirror surface viewed through a tube leading out of the cluster (see Fig. 5), a miniature hair hygrograph (*31*), and a thermoelectric aspiration psychrometer that uses only 30 milliliters of air (*5*) have been used.

In summer, at times when little water or nectar is being evaporated, the partial pressure of water vapor in the cluster may be only 3 to 4 mm-Hg above that of the outside air and may vary by less than 1 mm in different parts of the cluster. Under these circumstances the relative humidity varies with the temperature and is lowest in the brood area, where 40 to 50 percent has been recorded. At the other extreme, brood-nest relative humidities up to 70 percent have been recorded in an overheated colony where water was exposed to evaporation, and humidities up to 100 percent have been recorded in such a colony when the only aperture was a single bottom entrance (*4, 5*). Absolute humidity outside is positively correlated with temperature and is necessarily low in winter. Colonies kept in heated rooms in cold winter weather can have abnormally low relative humidities in the cluster (20 percent or less), and desiccation of larvae may prevent them from rearing brood.

In a colony kept outside in winter, the tight cluster hinders the escape of water vapor. An average partial pressure of 15 mm in the middle of the cluster has been recorded when the average outside was 7 mm. Cluster temperatures ranged from 20° to 30°C, giving relative humidities from about 85 to 50 percent. Brood reared in winter is protected from desiccation by dense clustering and low brood-nest temperature. The absolute humidity at the center of a winter cluster is well above the saturation level at the temperature of the cluster surface, but condensation rarely occurs in or near the cluster (*9*). Among the bees at the periphery of the cluster, partial pressures of water vapor seem to be close to those outside. Measurements (*31*) have shown 5 to 10 mm. Evidently there is a gradient of absolute humidity somewhere between the center of the cluster and the surface, and water vapor escapes by diffusion rather than by a through current of air. The fanning often heard in a winter cluster presumably keeps the absolute humidity fairly uniform throughout the loose central region, making conditions there like those in a summer cluster.

Cluster humidity is physiologically important to adult bees in winter as well as to brood at all times. Honey bees do not normally discharge their rectal contents in the nest, and when they are confined to the cluster by cold, they cannot obtain water should they require it, or discharge outside any surplus they accumulate. Forced discharge of rectal contents in the nest ("bee dysentery") can kill a colony. Surviving long periods of confinement, therefore, depends on a balance between water production from metabolism of food and water loss by evaporation from the bees' bodies. The balance is made possible by the dryness (15 to 20 percent moisture) of the winter food (honey).

Experiments with bees in a humidity "organ" analogous to the temperature organ showed some response to variation in humidity but no definite preferences (*32*). Apart from possible fanning at high humidities there is little evidence that a colony actively controls its humidity, though tight clustering in cold weather and water evaporation in hot weather tend to stabilize it.

Carbon Dioxide and Oxygen

The carbon dioxide concentration in samples of air withdrawn (through tubing of 1-millimeter bore) from various points in a cluster in summer has been estimated (*28*). The average was about 0.7 percent (by volume), and the maximum, 1.0 percent (2.3 percent in an observation hive). Up to 3 percent has been found (*33*) in summer and up to 6 percent in winter (*34*). A deduction from humidity measurements (*9*) and the proportion of carbon dioxide to water vapor produced by metabolism gives about 4 percent in winter, on the assumption that both gases leave the cluster by diffusion. Strong ventilation fanning has been obtained by artificially raising the carbon dioxide concentration to about 3.5 percent in summer, but the significance of this is doubtful as the fanning continued for some time after the carbon-dioxide concentration had returned to the original level (*28, 33*). The causes of ventilation fanning need to be investigated further.

Control of carbon dioxide or oxygen concentration may be unnecessary under natural conditions. Isolated bees do not visibly react to carbon dioxide concentrations of less than 10 percent or to oxygen concentrations of more than 7 percent (*35*).

Influence of Nest Cavity on Cluster Environment

Apis dorsata and *Apis florea*, the species of honey bee that nest entirely in the open and build a single comb suspended from a branch of a tree or other suitable overhanging surface, are confined to the tropics. *Apis cerana* of Asia and *Apis mellifera* of Europe and Africa, which are used by beekeepers and have subspecies adapted to temperate regions, build numerous parallel combs and normally nest in an enclosed space such as a hollow tree, a rock cavity, or some structure made by man. After swarming, however, they usually cluster temporarily on a branch of a tree and occasionally stay there and build combs. In favorable conditions, such a colony can live for some time; if protected from rain and predators, it might even survive a winter (*11*).

A colony in a cavity is sheltered from rain and direct solar radiation and needs only to guard the openings of the cavity to keep out predators and robber bees. Provision for security against robbers facilitates extensive storage of honey, as the cluster can move off filled areas of comb and extend the combs elsewhere. Ventilation of the colony is influenced by the nature of the cavity, the number and position of its openings, and the amount of space the cluster occupies. In a cavity with both upper and lower openings (for example, a hive with a bottom entrance and a ventilation hole at the top), air may pass upward by convection, or downward when bees are fanning at the bottom entrance. Air flows of 0.17 liter per second, by convection, and of 0.40 to 1.00 liter per second, by fanning, have been observed through such a hive (*28*). Air can flow through the cavity more easily when there is space between the cluster and the walls than when it must all go through the cluster. Some exchange by convection can occur when there is only a top aperture but not when there is only a bottom one. With a single aperture, wind and fanning can only increase ventilation by causing turbulence in the hive; air entering at one part of the entrance to replace air sucked out by fanning at another must take the shortest distance between the points of entry and exit (*36*). A fall in pressure of 2 mm of paraffin has been recorded when bees were fanning over the full width of the bottom entrance of an otherwise tightly sealed hive (*28*). Active ventilation of a cavity with a single entrance can be produced by bees fanning inside. In an observation hive with a long glass-covered entrance tunnel, chains of bees fanning round the inside of the hive outside the cluster, and parallel chains fanning in opposite directions in the entrance tunnel, have been seen.

The amount of thermal protection provided by the walls of the nest cavity has been much debated. Close contact with walls of low thermal conductivity may decrease cooling from part of the cluster surface and so make possible the formation of a larger cluster; also, for a given thickness of wall, the larger the cavity the larger its cooling surface must be. Thus, in spring, when brood rearing is limited by cluster size, breeding may be more rapid in a small cavity. One observer (*4*) has reported frequent temperature fluctuations of up to 6°C in the brood nest of a colony with much unoccupied space in its hive, but nobody else seems to have noticed anything of the kind; probably a colony can control its cluster temperature effectively in a cavity of any size.

It has been said (*11*) that in winter the temperature inside a hive but outside the cluster of bees is close to the temperature outside the hive (except after sudden changes in outside temperature). This may well be true if the hive entrance is big enough, and particularly if there is also a ventilator or an additional entrance at the top, but with small entrances and heavy insulation, differences as great as 25°C have been observed at very low outside temperatures (*8, 10*). Insulation in combination with entrance restriction can probably raise hive temperatures enough to have a substantial effect on heat loss from the cool outside surface of the cluster. There is some evidence (*37*) that, in very cold winter climates, the number of colonies that die because the bees cannot move to fresh food after emptying the combs within their reach is decreased by hive insulation.

Thermal protection may have disadvantages, however. By retarding penetration of heat during a sudden rise in outside temperature (*38*), it increases the likelihood that moisture will condense in the nest cavity and decreases the chance that the bees will get warm enough to fly to discharge their rectal contents. Both of these effects promote "dysentery," and condensation produces mouldy combs (*39*). However, as the bees produce about 5 times the amount of heat required to vaporize the amount of water they put out, under steady outside conditions condensation is not increased by restricting ventilation, so long as the proportion of heat passing through the walls of the nest cavity is negligible. Thus, insulation diminishes the amount of ventilation necessary or effective for decreasing condensation (*4*). The relative importance of these two ways in which thermal protection can influence the water metabolism of a colony seems not to have been assessed.

Where winters are cold, the advantages of thermal protection may outweigh the disadvantages, particularly as a moderate rise from a very low temperature can give little increase in absolute humidity or opportunity for flight. Where winters are mild, easy entry for heat may be more important. Experiments (*39*) indicate that when insulation is minimal very free ventilation is necessary to avoid condensation. Bees indigenous to the mountainous regions of the Caucasus, where winters are very cold, contract the entrances of their nests with propolis in the autumn, and bees of western Europe do not. This may be an adaptation to climatic conditions.

Conclusion

Colonies of honey bees can keep the temperature of their cluster within fairly narrow limits over a wide range of outside temperatures. High temperatures are avoided by fanning and evaporation of water. Control at low temperatures depends at least partly on the adjustment of heat loss by expansion and contraction of the cluster. The extent, if any, to which heat production is increased is still uncertain.

Little is known about whether the humidity and carbon dioxide content of the atmosphere of the cluster are controlled independently of temperature. The mechanism of temperature control also largely stabilizes humidity. The stimuli causing ventilation fanning need to be investigated further.

A nest cavity with walls of low thermal permeability and restricted ventilation may give a colony useful protection at very low winter temperatures, but this thermal protection also has disadvantages. In mild winters, poor ventilation can be dangerous.

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Data Processing by Optical Coincidence

This unconventional use of punched cards provides a flexible and rapid means for hand tabulation.

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The task of evaluating data is common to all sciences. Sometimes this problem can be readily solved, but when a study embraces more than a few variables, examination of the interrelationships between them poses technical difficulties. Even though we are working in an age of high-speed computers, there is a need for further development of readily available processing methods that will permit flexibility in analysis. Such flexibility facilitates the development, reformulation, and rapid follow-up of hypotheses. The present article offers one such technique, a method for storing data and obtaining cross tabulations. Among its specific advantages are the following: (i) convenience—there is no reliance on complex and bulky machines typical of central-office installations; time-consuming communications with processing personnel and the wait for return of data are eliminated; (ii) flexibility—the storage provides the equivalent of an IBM card with an infinite number of columns, and in subsequent processing, complex multivariate tables can be constructed with ease; (iii) speed—the method is faster than other hand-operated procedures for data tabulation; (iv) accuracy—simplicity of operation permits easy and frequent checks; (v) economy—economy of effort has already been mentioned; the economy of the technique in dollars and cents is equally striking. For example, in one application of this procedure, an outlay of approximately one dollar would enable the research worker to set up shop.

The method departs from procedures conventionally employed. Ordinarily the *individual* or the *case* serves as the basic conceptual entity—the central unit about which observations are collected. In the behavioral sciences, for example, we ask questions of the individual, we measure his responses, we observe his behavior (*1*). Having collected the data on a case-by-case basis, we then typically store it in the same fashion. The interview schedule, the case file, or other data constitute a record that may be preserved intact or may be evaluated in a variety of ways. When the research worker begins to summarize data on a considerable number of persons, he may for purposes of data processing set up a code sheet for each person included in a study, and may enter suitably coded information on each individual on one or more punched cards. Thus, in conventional procedures the unit for data collection, the individual, remains the unit for data storage.

The alternative method, with which we have been experimenting, employs as a basic principle one that has been profitably used in some bibliographic and indexing work in recent years (*2*). As used in indexing, the system inverts conventional procedures by using conceptual categories, rather than documents, as the units for storage. All documents are assigned code numbers, and concept cards (as opposed to document cards) are used for recording, in writing or by punched position, all documents pertaining to the concepts in question. Thus, to identify all documents which contain information in all of several specific concept areas, the appropriate concept cards are selected and the document numbers that appear on all the cards selected are obtained (*3*).

In applying this system to data analysis we use punched cards as a medium for storage, but again the system differs from conventional procedures, for the storage system is organized in terms of coded characteristics ("male," "female," "only child," "first born," "later born," and so on) rather than of individuals. There is a card for each characteristic, and each individual is assigned the same position on every card. If a given characteristic is associated with a particular individual, a punch is made in his specified position on the card for that characteristic. To illustrate, Card *A* in Fig. 1 has

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