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CURRENT PROBLEMS IN RESEARCH

Critical Periods in Behavioral Development

Critical periods determine the direction of social, intellectual, and emotional development.

J. P. Scott

A number of years ago I was given a female lamb taken from its mother at birth. My wife and I raised it on the bottle for the first 10 days of life and then placed it out in the pasture with a small flock of domestic sheep. As might have been expected from folklore, the lamb became attached to people and followed the persons who fed it. More surprisingly, the lamb remained independent of the rest of the flock when we restored it to the pasture. Three years later it was still following an independent grazing pattern. In addition, when it was mated and had lambs of its own it became a very indifferent mother, allowing its offspring to nurse but showing no concern when the lamb moved away with the other members of the flock (*1*).

Since following the flock is such a universal characteristic of normal sheep, I was impressed by the extensive and permanent modification of this behavior that resulted from a brief early experience. The results suggested that Freud was right concerning the importance of early experience, and pointed toward the existence of critical periods in behavioral development. As I soon discovered, there is considerable evidence that a critical period for determining early social relationships is a widespread phenomenon in vertebrates; such a critical period had long been known in ants (*2*).

The theory of critical periods is not a new one in either biology or psychology. It was strongly stated by Stockard in 1921, in connection with his experiments on the induction of monstrosities in fish embryos, although he gave credit to Dareste for originating the basic idea 30 years earlier (*3*). In experimenting with the effects of various inorganic chemicals upon the development of *Fundulus* eggs, Stockard at first thought one-eyed monsters were specifically caused by the magnesium ion. Further experiments showed him that almost any chemical would produce the same effect, provided it was applied at the proper time during development. These experiments and those of Child (*4*) and his students established the fact that the most rapidly growing tissues in an embryo are the most sensitive to any change in conditions, thus accounting for the specificity of effects at particular times.

Meanwhile Freud had attempted to explain the origin of neuroses in human patients as the result of early experience and had implied that certain periods in the life of an infant are times of particular sensitivity. In 1935, Lorenz (*5*) emphasized the importance of critical periods for the formation of primary social bonds (imprinting) in birds, remarking on their similarity to critical periods in the development of the embryo, and McGraw soon afterward (*6*) pointed out the existence of critical periods for optimal learning of motor skills in the human infant.

Since then, the phenomenon of critical periods has excited the imagination of a large group of experimenters interested in human and animal development. In describing this fast-moving scientific field, I shall point out some of the most significant current developments. More detailed information is available in some excellent recent reviews (*7*, *8*).

To begin with, three major kinds of critical-period phenomena have been discovered. These involve optimal periods for learning, for infantile stimulation, and for the formation of basic social relationships. The last of these has been established as a widespread phenomenon in the animal kingdom and consequently receives major attention in this article.

Periods Are Based on Processes

In the dog, the development of behavior may be divided into several natural periods marked off by important changes in social relationships (Table 1). Only a few other species have been studied in sufficient detail for making adequate comparisons, but enough data have been accumulated to show that similar periods can be identified in other mammals and in birds (*9*, *10*). I originally expected to find that the course of postnatal development, like that of embryonic development, would be essentially similar in all vertebrates, and that while the periods might be extended or shortened, the same pattern of development would be evident in all (*11*). However, comparison of only two species, man and the dog, shows that the periods can actually occur in reverse order, and that there is an astonishing degree of flexibility in behavioral development (*12*).

This leads to the conclusion that the important aspect of each developmental

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period is not time sequence but the fact that each represents a major developmental process. Thus, the neonatal period is chiefly characterized by the process of neonatal nutrition—nursing in mammals and parental feeding in many birds. The transition period is characterized by the process of transition to adult methods of nutrition and locomotion and the appearance of adult patterns of social behavior, at least in immature form. The period of socialization is the period in which primary social bonds are formed. If we consider processes alone, it is apparent that they are not completely dependent on each other and that they can therefore be arranged in different orders. It is also apparent that certain of these processes persist beyond the periods characterized by them. For example, a mammal usually retains throughout life the ability to suck which characterizes the neonatal period, although in most cases this ability is little used.

Process of Primary Socialization

Since one of the first acts of a young mammal is to nurse, and since food rewards are known to modify the behavior of adult animals, it once seemed logical to suppose that the process of forming a social attachment begins with food rewards and develops as an acquired drive. However, the experimental evidence does not support this extreme viewpoint. Brodbeck reared a group of puppies during the critical period of socialization, feeding half of them by hand and the other half by machine, but giving all of them the same degree of human contact (*13*). He found that the two sets of puppies became equally attached to people. This result was later confirmed by Stanley and his co-workers (*14*), who found that the only difference in response between the machine-fed and the hand-fed puppies was that the latter yelped more when they saw the experimenter. Elliot and King (*15*) fed all their puppies by hand but overfed one group and underfed another. The hungry puppies became more rapidly attached to the handlers. We can conclude that, in the dog, food rewards per se are not necessary for the process of socialization, but that hunger will speed it up.

Fisher (*16*) reared fox terrier puppies in isolation boxes through the entire socialization period. The puppies were fed mechanically (thus, food was entirely eliminated as a factor in the experiment), but they were removed from the boxes for regular contacts with the experimenter. One group of puppies was always rewarded by kind social treatment. A second group was sometimes rewarded and sometimes punished, but in a purely random way. Still a third group was always punished for any positive approach to the experimenter. The puppies that were both rewarded and punished showed most attraction and dependency behavior with respect to the experimenter, and the puppies that were always punished showed the least. After the treatment was discontinued, all the puppies began coming toward the experimenter, and the differences rapidly disappeared. This leads to the surprising conclusion that the process of socialization is not inhibited by punishment and may even be speeded up by it.

At approximately 3 weeks of age—that is, at the beginning of the period of socialization—young puppies begin to bark or whine when isolated or placed in strange places. Elliot and Scott (*17*) showed that the reaction to isolation in a strange place reaches a peak at 6 to 7 weeks of age, approximately the midpoint of the critical period, and begins to decline thereafter. Scott, Deshaies, and Morris (*18*) found that separating young puppies overnight from their mother and litter mates in a strange pen for 20 hours per day produced a strong emotional reaction and speeded up the process of socialization to human handlers. All this evidence indicates that any sort of strong emotion, whether hunger, fear, pain, or loneliness, will speed up the process of socialization. No experiments have been carried out to determine the effects of pleasant types of emotion, such as might be aroused by play and handling, but these were probably a factor in Brodbeck's experiment with machine-fed puppies.

The results of these experiments on dogs agree with evidence from other species. While they were going on, Harlow (*19*) was performing his famous experiments with rhesus monkeys isolated at birth and supplied with dummy "mothers." When given the choice between a comfortable cloth-covered mother without a nipple and an uncomfortable mother made of wire screening but equipped with a functional nursing bottle, the young rhesus monkeys definitely preferred the cloth-covered models from which they had received no food rewards. Harlow concluded that the acquired-drive theory of the origin of social attachment could be discarded.

Later, Igel and Calvin (*20*) performed a similar but more elaborate experiment with puppies. These animals had more opportunity to choose, being provided with four kinds of mother models: comfortable and uncomfortable, each type with and without nipples. Like rhesus monkeys, the puppies preferred the comfortable "mother" but usually chose one with a nipple. Thus, it appears that food rewards do contribute something to the social relationship, although they do not form its prime basis.

Since then Harlow (*21*) has raised to maturity the monkeys raised on dummy mothers, has mated them, and has observed their behavior toward their own young. They become uniformly poor mothers, neglecting their offspring and often punishing them when they cry. In spite of such rejection, the young rhesus infants desperately crawl toward their mothers and give every evidence of becoming attached to them, although perhaps not as strongly as in the normal relationship. Here again punishment does not inhibit the formation of a social bond.

The hypothesis that the primary social bond originates through food rewards had already been shown to be invalid in the precocial birds, many of which form attachments prior to the time when they begin to feed. Lorenz (*5*) was the first to point out the significance of this phenomenon, which he called "imprinting." He also stated that it differed from conditioning, primarily in that it was very rapid and apparently irreversible. However, rapid formation and great persistence are also characteristic of many conditioned responses and other learned behavior. Fabricius (*22*) pointed out that no sharp line can be drawn between imprinting and conditioning, and Collias (*23*) concluded that imprinting is a form of learned behavior that is self-reinforcing.

The process of imprinting in young ducklings and chicks has since been experimentally analyzed in much detail, with results that invariably confirm the conclusion that it takes place without any obvious external rewards or reinforcement. Hess (*24*) found that if he caused young ducklings to follow a model over varying distances or over

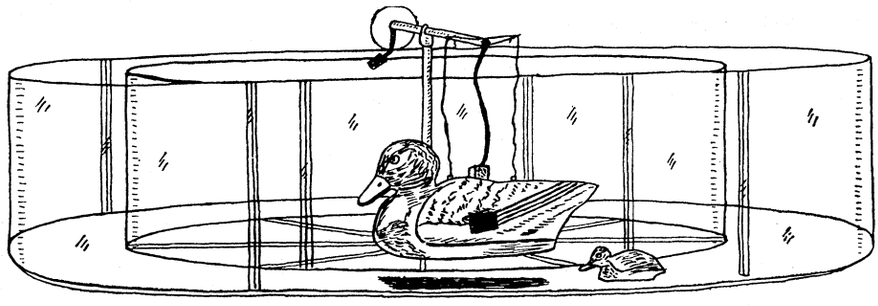

Fig. 1. Hess's apparatus for measuring the following response in ducklings and chicks. A decoy revolves on a circular path, the young duckling staying nearby. Other revolving objects may be substituted for the decoy, which is wired for sound. The following response is a major positive timing mechanism that initiates the critical period for imprinting; it is also an indicator that an attachment has been formed. [From a photo by E. H. Hess]

hurdles, the ducklings which had to make the greater effort became more strongly imprinted. He also found that the drug meprobamate and its congener carisoprodol, which are muscle relaxants as well as tranquilizers, greatly reduce imprinting if given during the critical period. James (*25*) found that chicks would become attached to an object illuminated by a flickering light, even though they were not allowed to follow, and Gray (*26*) later showed that they will become attached to a motionless object illuminated by a steady light and viewed from an isolation box. It is therefore apparent that chicks can become imprinted without following, although muscular tension may still be important.

Guiton (*27*) found that chicks allowed to follow a model in a group become less strongly imprinted than chicks exposed singly, and he attributed the results to the greater fear shown by the isolated chicks. Recently, Pitz and Ross (*28*) subjected young chicks following a model to a loud sound and found that this increased the speed with which they formed a social bond. Hess (*29*) (with the apparatus shown in Fig. 1) has given a mild electric shock to chicks following a model and finds that this also increases the strength of imprinting. Instead of avoiding the model, the distressed chick runs after it more closely.

We may conclude that these young birds become attached to any object to which they are long exposed during the critical period, even when their contact is only visual. We may also conclude that the speed of formation of a social bond is dependent upon the degree of emotional arousal, irrespective of the nature of that arousal. Whether attachment is the result of the emotion itself or of the reduction of emotion as the chick or duckling approaches the model is still a matter of conjecture (*30*).

Table 1. Periods of development in the puppy and song sparrow. The six periods of development described by Nice (*10*) for the song sparrow correspond to the first four periods in the puppy, as indicated in the table. The young of the two species are born or hatched in an immature state, require intensive parental care and feeding, and go through much the same stages before becoming independent. Development is much more rapid in the bird than in the puppy, although small mammals such as mice mature at about the same rate as birds.

Puppy			Song sparrow		
Name of period	Length of period (weeks)	Initial event	Name of period	Length of period (days)	Initial event
I. Neonatal	0–2	Birth, nursing	Stage 1 (nestling)	0–4	Hatching, gaping
II. Transition	2–3	Eyes open	Stage 2	5–6	Eyes open
III. Socialization	3–10	Startle to sound	Stage 3	7–9	Cowering—first fear reactions
			Stage 4 (fledgling)	10–16	Leaving nest—first flight
			Stage 5	17–28	Full flight
IV. Juvenile	10–	Final weaning	Stage 6 (juvenile)	29–	Independent feeding

Timing Mechanisms

The basic timing mechanisms for developmental periods are obviously the biological processes of growth and differentiation, usually called maturation. For various reasons, these are not precisely correlated with age from birth or hatching. For example, birds often retain newly formed eggs in their bodies overnight, thus incubating them for several hours before laying. By chilling duck eggs just before placing them in an incubator (thus killing all embryos except those in the earliest stages of development) Gottlieb (*31*) was able to time the age of ducklings from the onset of incubation rather than from hatching and found that variation in the timing for the critical period was much reduced. No such exact timing studies have been made in mammals, but I have estimated that there is at least a week's variation in development among puppies at 3 weeks of age, and the variation among human infants must be considerably greater (*32*).

Another approach to the problem is to try to identify the actual mechanisms which open and close a period. Since an important part of forming a primary social relationship appears to be emotional arousal while the young animal is in contact with another, it is obvious that the critical period for socialization could be timed by the appearance of behavioral mechanisms which maintain or prevent contact, and this indeed is the case. There are demonstrable positive mechanisms, varying from species to species, which bring young animals close to other members of their kind: the clinging response of young rhesus monkeys; the following response of chicks, ducklings, and lambs and other herd animals; the social investigation, tail wagging, and playful fighting of puppies; and the visual investigation and smiling of the human infant (*33*). These are, of course, accompanied by interacting responses from adult and immature members of the species: holding and clasping by primate mothers, brooding of mother hens and other birds, calling by mother sheep, investigation and play on the part of other young puppies, and the various supporting and nurturing activities of human mothers.

If contact and emotional arousal result in social attachment, there must be negative mechanisms which prevent such attachment once the critical period is past. Perhaps the most widespread of

these is the development of a fear response which causes the young animal to immediately leave the vicinity of a stranger and hence avoid contact. This developing fear response is found in young chicks (*7*), ducklings (*22, 34*), dogs (*35*; Fig. 2), rhesus monkeys (*36*), and in many other birds and mammals. Even in children there is a period between the ages of 5 and 12 months in which there is a mounting fear of strangers (*37*), sometimes called "8-months anxiety" (*38*). As already pointed out, there is a time in development when certain fear responses actually facilitate imprinting, but, as they grow stronger, the escape reaction follows so quickly that it prevents contact altogether.

Another sort of negative mechanism is the rejection of strange young by adult sheep, goats, and many other herd animals (*39*). In these species the mothers become strongly attached to the young within a few hours after birth and refuse to accept strangers thereafter (Fig. 3). This indicates that the rapid formation of emotional bonds is not limited to young animals.

These timing mechanisms all depend primarily on the development of social behavior patterns, but both sensory and motor development can also influence timing. For example, a very immature animal cannot maintain contact by following, and in slowly developing altricial birds such as jackdaws and doves (*5, 40*), the period of imprinting comes much later than it does in the precocial species. In the human infant the process of socialization begins before the adult motor patterns develop, but contact is maintained by visual exploration and by the smiling response to human faces (*33*). Thus, understanding the process of socialization and its timing mechanisms in any particular species requires a systematic study of the development of the various capacities which affect the time of onset and the duration of the critical period. These include sensory, motor, and learning capacities as well as the ability to perform essential patterns of social behavior.

The fact that emotional arousal is so strongly connected with the process of primary socialization suggests that the capacity to produce emotional reactions may also govern the time of onset of a critical period. Figure 4 summarizes the results of a study of emotional development in the dog during the critical period. If puppies are kept in large fields, totally isolated from people, fear and escape responses toward human beings very nearly reach a maximum by the time the puppies are 14 weeks old—a finding that fixes the upper limit of the period of socialization (*35*). On the other hand, the peak of the emotional response to isolation in a strange place occurs when puppies are approximately 6 to 7 weeks old, as does the peak of the heart-rate response to handling. At this age, such emotional arousal actually contributes to the strength of the social bond. Fuller (*41*) was unable to condition the heart-rate response consistently until puppies were 5 weeks old. This indicates that one of the factors that brings the critical period to a close may be the developing ability of the young puppy to associate fear responses with particular stimuli.

All this suggests that if the development of the escape response to strangers could be held in check, the critical period might be extended indefinitely. Raising puppies in small isolation boxes during the critical period inhibits the development of the escape response, but they still show obvious signs of fear when they are first removed from their cages. Fuller (*42*) reports some success in socializing these older pups by

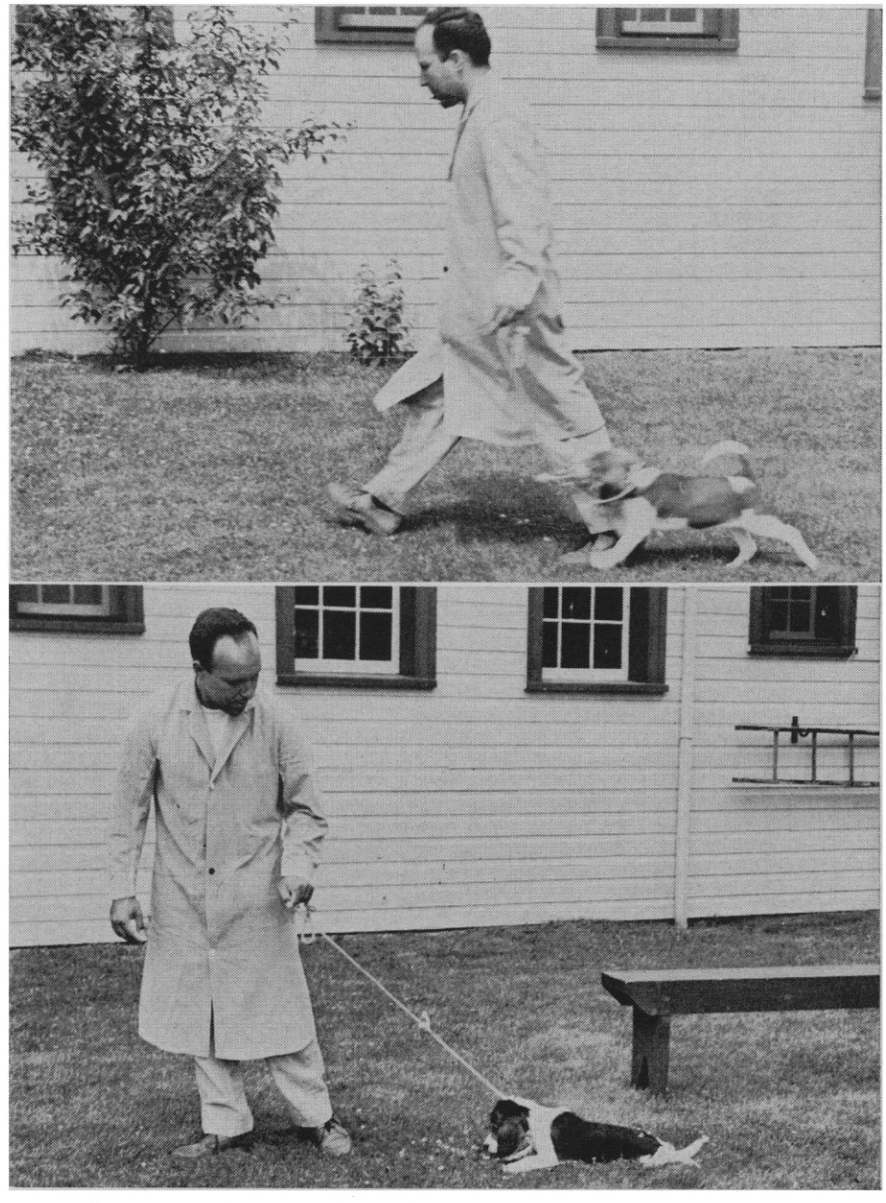

Fig. 2. Puppies reacting to leash training, according to their experience during the critical period (see *35*). (Top) Reaction of a puppy that had had contact with people for 1 week during the peak of the critical period. (Bottom) Reaction of a puppy that had had contact only with other dogs prior to the end of the critical period. This puppy shows an extreme fear reaction and refuses to follow.

overcoming their fear responses, either by careful handling or through the use of tranquilizing drugs.

Fear responses thus have the dual effect of facilitating the formation of the social bond during the critical period (along with other emotions) and of bringing the period to a close. This is understandable because the type of fear which terminates the critical period is a developing fear of strange animals. In the early part of the critical period the escape reaction is either lacking or is momentary and weak. At the close of the period it is strong enough to prevent contact altogether.

Formation of Affectional Bonds in Adult Life

Until recently, most investigators have concentrated their attention on the critical period for primary socialization or imprinting and few have gone on to study similar phenomena in later development. This field of investigation is just beginning to open up, though many related facts have long been known. For example, many birds form strong pair bonds which are maintained as long as both members survive. In studying the development of various types of social bonds in different species of ducks, Schutz (*43*) finds that, while attachments to particular individuals may be formed in the early critical period from 12 to 17 hours after hatching, the critical period for the attachment to the species may not come until sometime later, in some cases as late as 30 days after hatching, and the attachment to a particular member of the opposite sex, or the pair bond, does not come until the age of 5 months or so. Schutz also finds that female mallards cannot be sexually imprinted with respect to other species but always mate with other mallards no matter what their earliest experience has been. A similar phenomenon is reported by Warriner (*44*), who finds that male pigeons prefer to mate with birds whose color is similar to that of the parents who reared them, whether of the same or another color from themselves, but females show no preference.

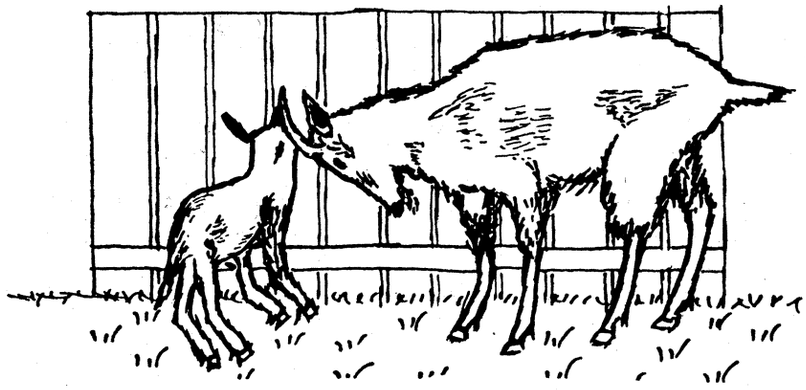

Fig. 3. Rejection by a mother goat of a kid not her own. The behavior of adults terminates the critical period for primary socialization in sheep and goats. Immediately after giving birth the mother will accept any young kid, but within a few hours she will reject any strange kid that approaches. [From a photo by A. U. Moore]

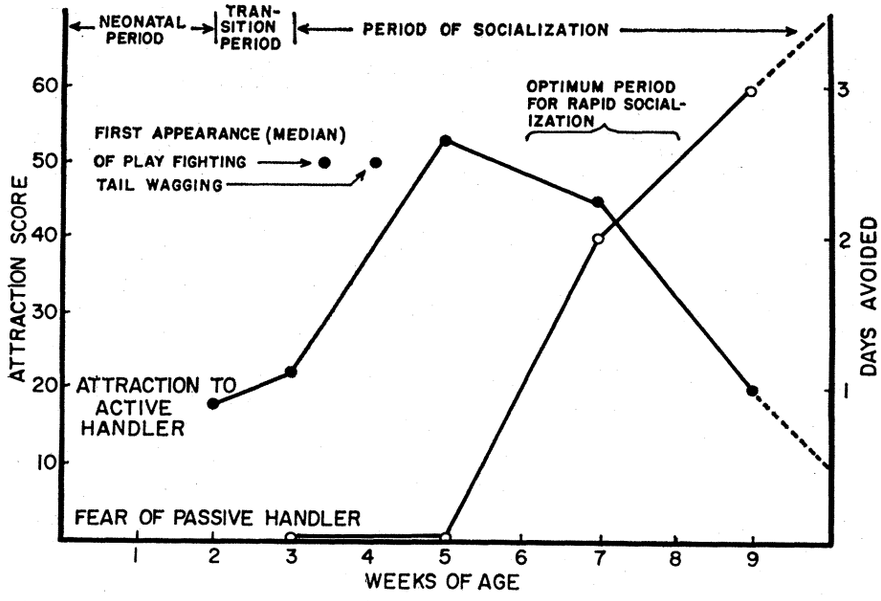

Fig. 4. Timing mechanisms for the critical period in puppies (see *35*). The period is initiated by positive behavior mechanisms, such as playful fighting, which result in attraction to a strange individual, and it is brought to a close by the development of a fear response which causes the attraction to decline. The optimum period for rapid and permanent socialization comes shortly after the appearance of prolonged avoidance reactions.

Certain species of mammals, such as foxes (*45*), form long-lasting mating bonds. It is possible that the violence of the sexual emotions contributes to the formation of the adult bond, just as other sorts of emotional arousal are important to the primary socialization of the infant. Klopfer (*46*) has suggested that the rapid formation of the social bond in a mother goat toward her kid is the result of the high degree of emotional arousal which accompanies the birth of the offspring.

In short, it seems likely that the formation of a social attachment through contact and emotional arousal is a process that may take place throughout life, and that although it may take place more slowly outside of certain critical periods, the capacity for such an attachment is never completely lost.

At this point it may be remarked that, in attempting to analyze the development of affection and social bonds objectively, scientists have often tried to simplify the problem by postulating various unitary, unromantic, and sometimes unesthetic explanations. One of these was the "acquired drive" hypothesis—that children love you because you feed them. Taking a more moderate view Harlow (*19*) has emphasized "contact comfort" as a major variable —that the young monkey begins to love its mother because she feels warm and comfortable—but that a number of other factors are involved. As this article indicates, evidence is accumulating that there is a much less specific, although equally unromantic, general

mechanism involved—that given any kind of emotional arousal a young animal will become attached to any individual or object with which it is in contact for a sufficiently long time. The necessary arousal would, of course, include various specific kinds of emotions associated with food rewards and contact comfort.

It should not be surprising that many kinds of emotional reactions contribute to a social relationship. The surprising thing is that emotions which we normally consider aversive should produce the same effect as those which appear to be rewarding. This apparent paradox is partially resolved by evidence that the positive effect of unpleasant emotions is normally limited to early infancy by the development of escape reactions.

Nevertheless, this concept leads to the somewhat alarming conclusion that an animal (and perhaps a person) of any age, exposed to certain individuals or physical surroundings for any length of time, will inevitably become attached to them, the rapidity of the process being governed by the degree of emotional arousal associated with them. I need not dwell on the consequences for human behavior, if this conclusion should apply to our species as well as to other animals, except to point out that it provides an explanation of certain well-known clinical observations such as the development by neglected children of strong affection for cruel and abusive parents, and the various peculiar affectional relationships that develop between prisoners and jailors, slaves and masters, and so on. Perhaps the general adaptive nature of this mechanism is that since the survival of any member of a highly social species depends upon the rapid development of social relationships, a mechanism has evolved which makes it almost impossible to inhibit the formation of social bonds.

Critical Periods of Learning

Unlike the process of socialization, the phenomenon of critical periods of learning was first noticed in children rather than in lower animals. McGraw's (*47*) famous experiment with the twins Johnny and Jimmy was a deliberate attempt to modify behavioral development by giving one of a pair of identical twins special early training. The result varied according to the activity involved. The onset of walking, for example, was not affected by previous practice or help. Other activities, however, could be greatly speeded up—notably roller skating, in which the favored twin became adept almost as soon as he could walk. In other activities performance was actually made worse by early practice, simply because of the formation of unskillful habits. McGraw (*6*) concluded that there are critical periods for learning which vary from activity to activity; for each kind of coordinated muscular activity there is an optimum period for rapid and skillful learning.

In an experiment with rats, Hebb (*48*) used the technique of providing young animals with many opportunities for spontaneous learning rather than formal training. Pet rats raised in the rich environment of a home performed much better on learning tasks than rats reared in barren laboratory cages. Since then, other experimenters (*49*) have standardized the "rich" environment as a large cage including many objects and playthings and have gotten similar effects.

Forgays (see *50*) finds that the age at which the maximum effect is produced is limited to the period from approximately 20 to 30 days of age, immediately after weaning. A similar experience in adult life produces no effect. In rats, at any rate, the critical period of learning seems to coincide with the critical period of primary socialization, and it may be that the two are in some way related. Candland and Campbell (*51*) find that fearful behavior in response to a strange situation begins to increase in rats between 20 and 30 days after birth, and Bernstein (*52*) showed earlier that discrimination learning could be improved by gentle handling beginning at 20 days. It may well be that the development of fear limits the capacity for future learning as well as the formation of social relationships.

In addition to these studies on motor learning and problem solving, there are many experiments demonstrating the existence of critical periods for the learning of social behavior patterns. It has long been known that many kinds of birds do not develop the characteristic songs of their species if they are reared apart from their own kind (*53*). More recently, Thorpe (*54*) discovered a critical period for this effect in the chaffinch. If isolated at 3 or 4 days of age, a young male chaffinch produces an incomplete song, but if he hears adults singing, as a fledgling 2 or 3 weeks old or in early juvenile life before he sings himself, he will the next year produce the song characteristic of the species, even if he has been kept in isolation. In nature, the fine details of the song are added at the time of competition over territory, within a period of 2 or 3 weeks, when the bird is about a year old. At this time it learns the songs of two or three of its neighbors, and never learns any others in subsequent years. The critical period for song learning is thus a relatively long one, but it is definitely over by the time the bird is a year old. There is no obvious explanation for its ending at this particular time, but it is possible that learning a complete song pattern in some way interferes with further learning.

King and Gurney (*55*) found that adult mice reared in groups during youth fought more readily than animals isolated at 20 days of age. Later experiments showed that most of the effect was produced in a 10-day period just after weaning, and that similar experience as adults produced little or no effect (*56*). Thus, there appears to be a critical period for learning to fight through social experience, and this experience need be no more than contact through a wire. In this case the effect is probably produced by association with other mice before the fear response has been completely developed. Similarly, Fisher (*16*) and Fuller (*57*) inhibited the development of attacking behavior in fox terriers by raising them in isolation through the critical period for socialization. The animals would fight back somewhat ineffectually if attacked, but did not initiate conflicts. Tinbergen (*58*) found a critical period in dogs for learning territorial boundaries, coinciding with sexual maturity.

The results of corresponding experiments on sexual behavior vary from species to species. In mice, rearing in isolation produced no effects (*59*). Beach (*60*) found that male rats reared with either females or males were actually slower to respond to sexual behavior than isolated males, and he suggested that habits of playful fighting established by the group-reared animals interfered with sexual behavior later on. In guinea pigs, contact with other young animals improves sexual performance (*61*).

On the other hand, young chimpanzees (*62*) reared apart from their kind can only be mated with experienced animals. Harlow (*21*) discovered that his rhesus infants reared on

dummy mothers did not develop normal patterns of sexual behavior, and he was able to obtain matings only by exposing females to experienced males (Fig. 5). Normal behavior can be developed by allowing 20-minute daily play periods with other young monkeys, but if rhesus infants are reared apart from all other monkeys beyond the period when they spontaneously play with their fellows, patterns of both sexual and maternal behavior fail to develop normally. These results suggest that play has an important role in developing adult patterns of social behavior in these primates, and that the decline of play behavior sets the upper limit of the critical period during which normal adult behavior may be developed.

Such great changes in the social environment rarely occur in humans even by accident, but Money, Hampson, and Hampson (*63*) have studied the development of hermaphroditic children who have been reared as one sex and then changed to the other. They find that if this occurs before 2½ years of age, very little emotional disturbance results. Thus, there is a critical period for learning the sex role, this capacity persisting unchanged up to a point in development which roughly corresponds to the age when children begin to use and understand language. Perhaps more important, this is the age when children first begin to take an interest in, and play with, members of their own age group.

It is difficult to find a common factor in these critical periods for learning. In some species, such as rats, mice, dogs, and sheep, certain critical periods for learning coincide with the period for primary socialization and seem to be similarly brought to a close by the development of fear reactions. Other critical periods, in chaffinches and dogs, coincide with the formation of adult mating bonds. However, the critical period for sexual learning in the rhesus monkey comes later than that for primary socialization (*64*), as do critical periods for various kinds of learning in human beings.

Part of this apparent inconsistency arises from our ignorance regarding timing mechanisms. One such mechanism must be the development of learning capacities, and we have evidence in dogs (*65*), rhesus monkeys (*66*), and human infants (*12*) that learning capacities change during development, sometimes in a stepwise fashion. One element in these capacities is the ability to learn things which facilitate subsequent learning.

It is equally possible, however, to "learn not to learn," and such a negative learning set may act to bring the critical period to a close. At this point, we can only state a provisional general hypothesis: that the critical period for any specific sort of learning is that time when maximum capacities—sensory, motor, and motivational, as well as psychological ones—are first present.

Critical Periods for Early Stimulation

Experiments to determine the effects of early stimulation have been mainly performed on infant mice and rats, which are usually weaned at about 21 days at the earliest, and have been concerned with the effect of stimulation during this pre-weaning period. All investigators beginning with Levine (*67*) and Schaefer (*68*), agree that rats handled during the first week or 10 days of life have a lessened tendency to urinate and defecate in a strange "open field" situation, learn avoidance behavior more readily, and survive longer when deprived of food and water. In short, early stimulation produces an animal that is less timorous, learns more quickly, and is more vigorous. Levine found that the effect could be obtained by a variety of stimuli, including electric shock and mechanical shaking as well as handling. This ruled out learned behavior as an explanation of the effect, and Levine, Alpert, and Lewis (*69*) discovered that animals handled in the early period showed a much earlier maturation of the adrenocortical response to stress. Levine interpreted these results as indicating that the laboratory environment did not provide sufficient stimulation for the proper development of the hormonal systems of the animals. This interpretation is in agreement with Richter's finding (*70*) that laboratory rats are quite deficient in adrenocortical response as compared with the wild variety.

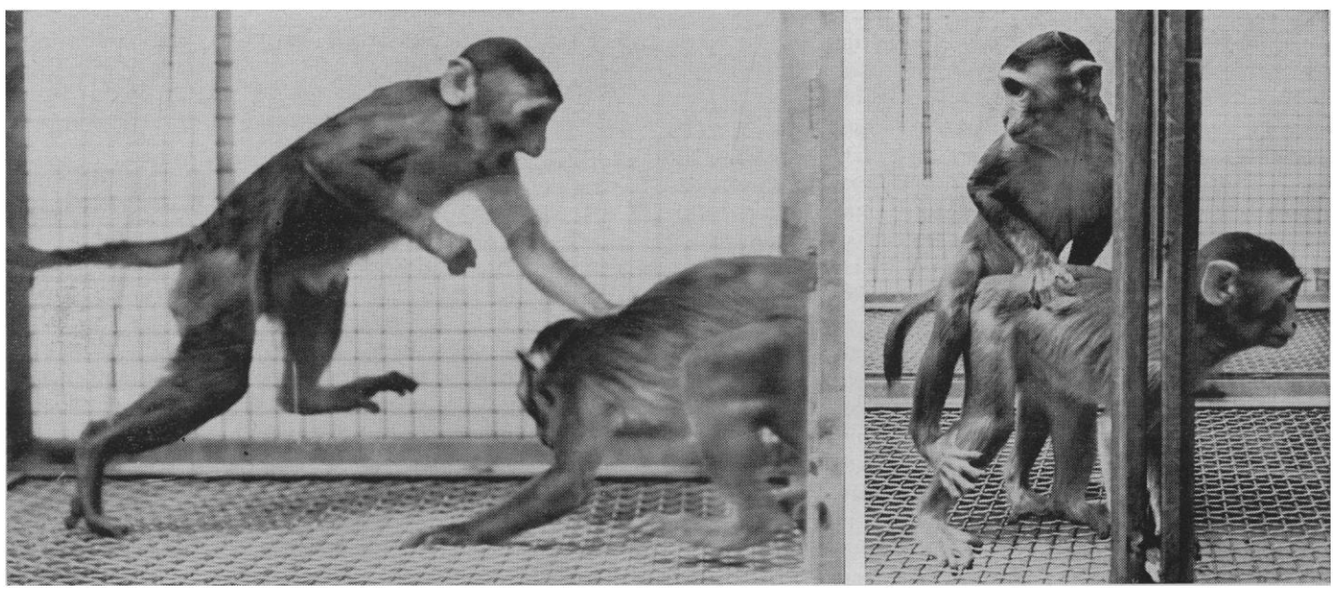

Fig. 5. Through play behavior during a critical period young rhesus monkeys develop the capacity for adult sexual behavior. The two at right exhibit an approximation of the adult posture. It is almost impossible to mate monkeys raised with cloth "mothers" without an opportunity for play with other infants. [H. F. Harlow]

Schaefer, Weingarten, and Towne (*71*) have duplicated Levine's results by the use of cold alone, and have suggested temperature as a possible unitary mechanism. However, their findings are not necessarily in disagreement with those of Levine, as the hormonal stress response can be elicited by a variety of stimuli, and temperature may simply be another of the many kinds of stimuli which produce the effect.

According to Thompson and Schaefer (*72*) the earlier the stimulation the greater the effect. If the hormonal mechanism is the chief phenomenon involved, we can say that there is a critical period during the first week or 10 days of life, since the adrenal response in any case matures and becomes fixed by 16 days of age.

Denenberg (*73*) takes a somewhat different approach, pointing out that there should be optimal levels of stimulation, so that either very weak or very strong stimulation would produce poor results. He suggests that there are different critical periods for the effect of early stimulation, depending on the intensity of stimulation and the kind of later behavior measured. Working within the critical first 10 days, Denenberg found that the best avoidance learning was produced by stimulation in the second half of the period, whereas the best survival rates were produced by stimulation in the first half. Weight was approximately equally affected, except that there was little effect in the first 3 days (*74*).

Analyzing the effect on avoidance learning, Denenberg (*75*) and his associates found that both unhandled controls and rats handled for the first 20 days performed poorly, the former because they were too emotional and the latter because they were too calm to react quickly. An intermediate amount of emotional response produces the best learning, and this can be produced by handling only in the first 10 days of life; handling during the second 10 days has a lesser effect. No handling produces too much emotionality, and handling for 20 days results in too little. Irrespective of the effect on learning, the data lead to the important conclusion that emotional stimulation during a critical period early in life can lead to the reduction of emotional responses in later life.

More precisely, there appear to be two critical periods revealed by research on early stimulation of rats, one based on a physiological process (the development of the adrenal cortical stress mechanism) and extending to 16 days of age at the latest, the other based on a psychological process (the reduction of fear through familiarity) (*51*), beginning about 17 days when the eyes first open and extending to 30 days. The effects of handling during these two periods are additive, and many experiments based on arbitrary time rather than developmental periods undoubtedly include both.

The deleterious effects of excessive stimulation in the life of the infant may also be interpreted as a traumatic emotional experience. Bowlby (*76*), in studying a group of juvenile thieves, found that a large proportion of them had been separated from their mothers in early infancy, and he postulated that this traumatic emotional experience had affected their later behavior. Since this conclusion was based on retrospective information, he and his coworkers have since studied the primary symptoms of separation and have described in detail the emotional reactions of infants sent to hospitals, and thus separated from their mothers (*77*). Schaffer (*78*) found a difference in reaction to separation before 7 months and separation afterward. Both sets of infants were disturbed, but they were disturbed in different ways. Infants show increasingly severe emotional reactions to adoption from 3 through 12 months of age (*33*). It seems logical to place the beginning of the critical period for maximum emotional disturbance at approximately 7 months—at the end of the critical period for primary socialization, which Gray (*79*) places at approximately 6 weeks to 6 months. Infants whose social relationships have been thoroughly established and whose fear responses toward strangers have been fully developed are much more likely to be upset by changes than infants in which these relationships and responses have not yet been developed.

However, not all apparently "traumatic" early experiences have such a lasting effect. Experimental work shows that young animals have a considerable capacity to recover from unpleasant emotions experienced in a limited period in early life (*80*), and that what is traumatic in one species may not be in another. While young rats become calmer after infantile stimulation, young mice subjected to excessive auditory stimulation later become more emotional (*81*). At this point it is appropriate to point out that critical periods are not necessarily involved in every kind of early experience. Raising young chimpanzees in the dark produces degeneration of the retina, but this is a long and gradual process (*82*).

Another approach to the problem is to stimulate emotional responses in mothers and observe the effect on the offspring. Thompson (*83*) and other authors (*84*) have shown that the offspring of rats made fearful while pregnant are more likely to be overemotional in the open-field situation than the offspring of animals not so stimulated. Since any direct influence of maternal behavior was ruled out by cross-fostering experiments, it seems likely that the result is produced by modification of the adrenocortical stress mechanism—in this case, by secretion of maternal hormones acting on the embryo rather than by stimulation after birth of the young animal itself. No precise critical period for the effect has been established, but it is probably confined to the latter part of pregnancy. Similar effects have been obtained in mice (*85*), and if such effects can be demonstrated in other mammals, the implications for prenatal care in human beings are obvious.

It is interesting to note that, whereas shocking the mother both before and after parturition has the effect of increasing emotional responses in the young, the emotional responses of young rats are *decreased* when the treatment is applied directly to them. The explanation of this contradiction must await direct experiments on the endocrine system.

General Theory of Critical Periods

There are at least two ways in which experience during critical periods may act on behavioral development. The critical period for primary socialization constitutes a turning point. Experience during a short period early in life determines which shall be the close relatives of the young animal, and this, in turn, leads the animal to develop in one of two directions—the normal one, in which it becomes attached to and mates with a member of its own species, or an abnormal one, in which it becomes attached to a different species, with consequent disrupting effects upon sexual and other social relationships with members of its own kind.

The concept of a turning point ap-

plies equally well to most examples of critical periods for learning. Up to a certain point in development a chaffinch can learn several varieties of song, but once it has learned one of them it no longer has a choice. Similarly, the human infant can learn either sex role up to a certain age, but once it has learned one or the other, changing over becomes increasingly difficult. What is learned at particular points limits and interferes with subsequent learning, and Schneirla and Rosenblatt (*86*) have suggested that there are critical stages of learning—that what has been learned at a particular time in development may be critical for whatever follows.

A second sort of action during a critical period consists of a nonspecific stimulus producing an irrevocable result, not modifiable in subsequent development. Thus, almost any sort of stimulus has the effect of modifying the development of the endocrine stress mechanism of young rats in early infancy.

Is there any underlying common principle? Each of these effects has its counterpart in embryonic development. Up to a certain point a cell taken from an amphibian embryo and transplanted to a new location will develop in accordance with its new environment. Beyond this turning point it develops in accordance with its previous location. Some cells retain a degree of lability, but none retain the breadth of choice they had before. Similarly, specific injuries produced by nonspecific causes are also found in embryonic development: damage to an embryonic optic vesicle results in a defective eye, no matter what sort of chemical produces the injury. It is obvious that the similarity between this case and the critical period for early stimulation can be accounted for by the single common process of growth, occurring relatively late in development in the case of the endocrine stress mechanism and much earlier in the development of the eye. The effects are nonspecific because of the fact that growth can be modified in only very limited ways, by being either slowed down or speeded up.

Both growth and behavioral differentiation are based on organizing processes. This suggests a general principle of organization: that once a system becomes organized, whether it is the cells of the embryo that are multiplying and differentiating or the behavior patterns of a young animal that are becoming organized through learning, it becomes progressively more difficult to reorganize the system. That is, organization inhibits reorganization. Further, organization can be strongly modified only when active processes of organization are going on, and this accounts for critical periods of development.

Conclusion

The concept of critical periods is a highly important one for human and animal welfare. Once the dangers and potential benefits for each period of life are known, it should be possible to avoid the former and take advantage of the latter.

The discovery of critical periods immediately focuses attention on the developmental processes which cause them. As these processes become understood, it is increasingly possible to deliberately modify critical periods and their results. For example, since the development of fear responses limits the period of primary socialization, we can deliberately extend the period by reducing fear reactions, either by psychological methods or by the use of tranquilizing drugs. Or, if it seems desirable, we can increase the degree of dependency of a child or pet animal by purposely increasing his emotional reactions during the critical period. Again, if infantile stimulation is desirable, parents can be taught to provide it in appropriate amounts at the proper time.

Some data suggest that for each behavioral and physiological phenomenon there is a different critical period in development. If this were literally true, the process of development, complicated by individual variability, would be so complex that the concept of critical periods would serve little useful purpose. Some sort of order can be obtained by dealing with different classes of behavioral phenomena. For example, it can be stated that the period in life in which each new social relationship is initiated is a critical one for the determination of that relationship. Furthermore, there is evidence that critical-period effects are more common early in life than they are later on, and that the critical period for primary socialization is also critical for other effects, such as the attachment to particular places (*87*), and may overlap with a critical period for the formation of basic food habits (*88*).

We may expect to find that the periods in which actual physiological damage through environmental stimulation is possible will turn out to be similarly specific and concentrated in early life.

A great deal of needed information regarding the optimum periods for acquiring motor and intellectual skills is still lacking. These skills are based not merely on age but on the relative rate of maturation of various organs. Any attempt to teach a child or animal at too early a period of development may result in his learning bad habits, or simply in his learning "not to learn," either of which results may greatly handicap him in later life. In the long run, this line of experimental work should lead to greater realization of the capacities possessed by human beings, both through avoidance of damaging experiences and through correction of damage from unavoidable accidents (*89*).

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Stockpiling to Survive a Nuclear Attack

The second phase of a total defense system must bridge the gap until production facilities are restored.

Albert W. Bellamy

It is convenient to consider nonmilitary defense systems in two broad categories: (i) casualty prevention during the acute phase of an attack and (ii) casualty prevention and the acceleration of national recovery during the much longer postattack period. Both categories have the same objective, national survival, but I mention them separately as distinctive phases requiring quite different resposes from the people.

In the event of an attack the acute effects of blast and heavy radioactive contamination may last about two weeks. Preparation for this period is being emphasized officially. Shelters, emergency supplies, communications capability, instrumentation for detecting and measuring environmental pollutants, organization, and training are part of the program.

The second phase is likely to extend over a period variously estimated as from a few months to a number of years. For survival during this phase the defense system should include a reserve of supplies essential for bridging the gap between the destruction of critically important production facilities and their restoration. These supplies must be assembled in advance in selected locations, so that they will be available when and where they are needed, without having to be distributed by powered vehicles. The capability to maintain the surviving population in a state of physical and mental health and able to get ahead rapidly with the work of restoration is of overriding importance in any recovery program.

The best defense is, of course, the prevention of an attack. We must, however, consider the variables that would lessen casualties and facilitate the production of food and industrial goods if a heavy attack with nuclear weapons should be made on the United States. The total recovery operation would be highly complex and would call for systematic study of many factors, but here I am concerned primarily with the problem of food supply after an attack.

While giving much personal thought to the matter, I have drawn freely on the several studies that have been made of the estimated destructive and disruptive effects of a heavy attack (*1*). There is general agreement that such

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