

Destabilizing selection as a factor in domestication

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I SHOULD LIKE to express my deep gratitude to the American Genetic Association for the honor of being invited to deliver the Wilhelmine E. Key lecture. I am delighted to accept this invitation as an expression of the international cooperation of scientists, which is indispensable for the progress of science and of life itself.

It is rightly believed that the domestication of animals, whose history does not count more than 15 thousand years, is one of the greatest biological experiments. The main result of domestication has been an enormous increase in the rate and range of variability of the domesticated species. Domestic animals differ from their wild ancestors, and from each other, much more than do some species and even genera. The history of evolution does not reveal any similar variability developing within such a short period of time. These observations have made some scientists doubt the applicability of the laws of Darwinian evolution to the process of domestication.

Different species of domestic animals, although belonging to remote systematic groups (not only genera or families, but even orders), nevertheless exhibit a homologous variability with respect to many phenotypic features. N.I. Vavilov, who was the first to formulate the principle of homologous variability¹⁶, attributed a great general biological significance to it. Under the conditions of domestication, this principle manifests itself with a special clarity. In particular, all domestic animals have lost their strict seasonal patterns of reproduction and moulting and tend to reproduce at any time of the year. This phenomenon is difficult to explain, because the heritability of the traits characteristic of the seasonal rhythm of activity of wild animals is practically zero. Under domestication, fertility has greatly increased, and many new morphological and physiological characters have appeared, which are similar (homologous) in different systematic groups and some of which have a dominant mode of inheritance.

In analyzing various aspects of this problem about 20 years ago, I formulated the hypothesis that the loss of the strict seasonal rhythm of reproduction and of the mono-estrous condition inherent in wild animals was a conse-

quence of selection for the domesticated type of behavior at the very beginning of selection.

Domesticated Behavior

What do I mean by domesticated behavior?

The main criterion here is the ability of animals to have direct contact with man, not to be afraid of man, to obey him, and to reproduce under the conditions created by him, which constitutes the necessary conditions for the economical use of animals. It is obvious that selection for behavior has been unconsciously carried out by man since the earliest stages of animal domestication.

To test this hypothesis, I started an experiment more than 20 years ago on the domestication of silver foxes bred on special farms for the sake of their fur. This experiment, now in collaboration with Dr. L. Trut, is still in progress on the experimental farm of our Institute. Although the fox has now been bred in captivity for 80 years, it has preserved the seasonal biology characteristic of wild species: mono-estrousness, a strict seasonal rhythm of reproduction, and moulting.

A special study⁵ we made at the first stage of our work demonstrated that in farm-bred fox populations, which have never undergone any special selection for behavior, there is a certain polymorphism with respect to their characteristic response to man. Among the animals studied by us, about 30 percent were extremely aggressive towards man, 20 percent were fearful, 40 percent were aggressively fearful, and only 10 percent displayed a quiet exploratory reaction without either fear or aggression. However, even the nonaggressive foxes could not be handled without special precautions against bites, so that they, too, were virtually wild animals. Each of the three types of reaction to man varied in its manifestation.

In this study, some facts corroborating indirectly my hypothesis were found: 1) it was demonstrated that the type of defense behavior towards man, which is formed during the first 2–2½ months of life is preserved in most of the animals as a permanent individual characteristic whose repeatability is very high: $r = 0.85$; 2) variability in the defense behavior has a hereditary basis, and thus selection is possible; 3) a phenotypic and a genotypic correlation was found between the type of defensive behavior of females and the time of onset of their reproductive activity within the breeding season. In females with relatively tame behavior, the activation of reproductive function and mating took place earlier (late January to late

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March) within the reproductive season than in females of other behavior types⁶. Due to this correlation, a selection for tame behavior could shift the time of onset of reproductive activity outside the normal breeding season and, possibly, could identify those animals capable of reproducing twice a year (i.e., render them di-estrous).

The main task of the experiment was, by means of selection for tame behavior, to obtain animals similar in their behavior to the domestic dog. That is why it was natural that the main selection criterion was the reaction of foxes to human contact.

The foxes were evaluated by their reaction to a person's approach at several different ages. The first test was made not later than 2-2½ months of age, with the young maintained in cages by groups. Evaluated was the animal's reaction to the experimenter's attempt to touch it or to give it food. For further observation and study, animals that displayed a relatively tame and interested attitude towards this procedure were selected, while aggressive or fearful animals were discarded. At a later age (4 to 5 months), tests were made with animals having unrestrained freedom to move about in special enclosures. Again, the reaction of animal to experimenter, the foxes disposition to approach the person who stayed in the enclosure, was recorded.

For breeding, animals were selected that consistently displayed tame behavior with respect to people. Later,

the selection was restricted to those animals that were actively willing to contact the experimenter. The selection was strict, and included not more than 15-20 percent of the tested animals.

In the experiments, a system of homogenous crosses with respect to behavior was used, while at the same time the selected population was maintained by outbreeding in order to minimize homozygosity due to inbreeding. From time to time animals selected for behavior from different farms and not related to each other were introduced into the experimental population. The level of homozygosity in the experimental population was maintained at no more than 2-5 percent. Inbreeding was used only in special cases to produce desired genotypes. More than 10,000 foxes have been tested for behavior during these experiments. The degree of domesticated behavior, or of aggressiveness, was estimated on a scale running from 1 to 4. I shall not dwell on the genetic analysis of behavior here, but the selection was quite effective (Figure 1). At present, about 500 adult females, 150 males, and over 2000 young foxes have been obtained by these selection procedures.

The animals of the experimental population differ sharply in their behavior from the foxes bred on farms where no selection is practiced and from those foxes of the initial unselected population (Figure 2). The foxes of the selected population not only are not afraid of people,

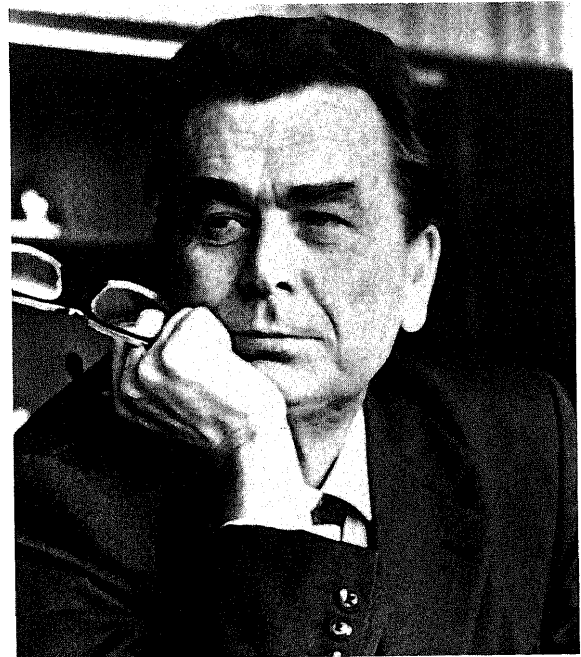
DMITRY K. BELYAEV was born in 1917 into the family of a clergyman in the village of Protasovo in the Kostroma region of the USSR, 350 km north of Moscow. He spent his early childhood in Protasovo, then went to Moscow where he completed his secondary school education. In 1939 he graduated from the zootechnical faculty of the Ivanovo Agricultural Institute and started his work in the Department of Genetics and Selection of the Laboratory of Fur-Bearing Animal Breeding in Moscow. His training in genetics and in the theory of selection was guided by Professors A.I. Panin and B.N. Vasin.

Dr. Belyaev served in the Second World War during the years 1941-1945, first as a soldier and then as an officer of the Soviet Army. At the end of 1945 he returned to his work in the Laboratory and in 1946 he was awarded the Ph.D. degree.

In 1958 Dr. Belyaev moved from Moscow to Novosibirsk, when the Siberian Branch of the USSR Academy of Sciences was organized. In 1958-1959 he was the Head of the Department of Animal Genetics at the Institute of Cytology and Genetics, and in 1960 became the Director of this institute, the position he presently holds. In 1964 he was elected a corresponding member and in 1972 a permanent member of the USSR Academy of Sciences. In 1975 he became a Vice President of the Siberian Branch of the USSR Academy of Sciences. Since 1968, he has been the Chairman of the Scientific Council on the Problems of Genetics and Breeding of the USSR Academy of Sciences.

Dr. Belyaev's work has been mainly in genetics and in the theory and practice of animal breeding. Some of his research also has focused on the role of photoperiodism in the regulation of the functions of mammals, including moulting and fur formation, embryonic diapause, and embryonic mortality.

He is married and has three sons.



He served as Secretary General of the XIV International Congress of Genetics held in Moscow in 1978, and is currently President of the International Genetics Federation.

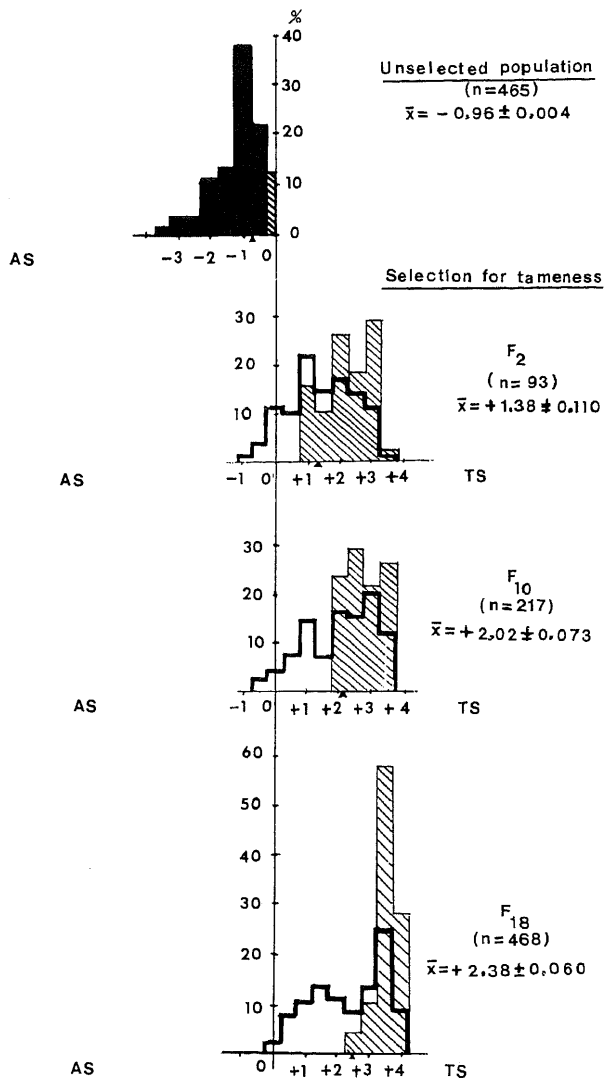


FIGURE 1—The distribution of foxes of different generations of selection for tameability according to scores achieved on behavior tests. The top histogram shows the distribution of the nonselected population. The hatched area signifies the initial population used for selection. In the following histograms the distribution of the F_2 , F_{10} , and F_{18} generations is outlined by a solid line. The hatched area signifies the distribution of only that part of the generation that was used for further selection for tameability. The arrow shows the mean point of behavior either of the whole control population (top histograms) or of the whole progeny of the F_2 , F_{10} , F_{18} generations. (AS = aggressive score; TS = tameness score.)

but they display an active positive reaction to human contact, and answer to their nicknames. Such foxes are quite tame, not as a result of training or taming, but due to prolonged selection for a tame genotype. Moreover, some quite new ethological characters have appeared, unusual even in the tamest animals bred on ordinary farms. Like dogs, these foxes seek contact with familiar persons, tend to get close to them, and lick their hands and faces. In mo-

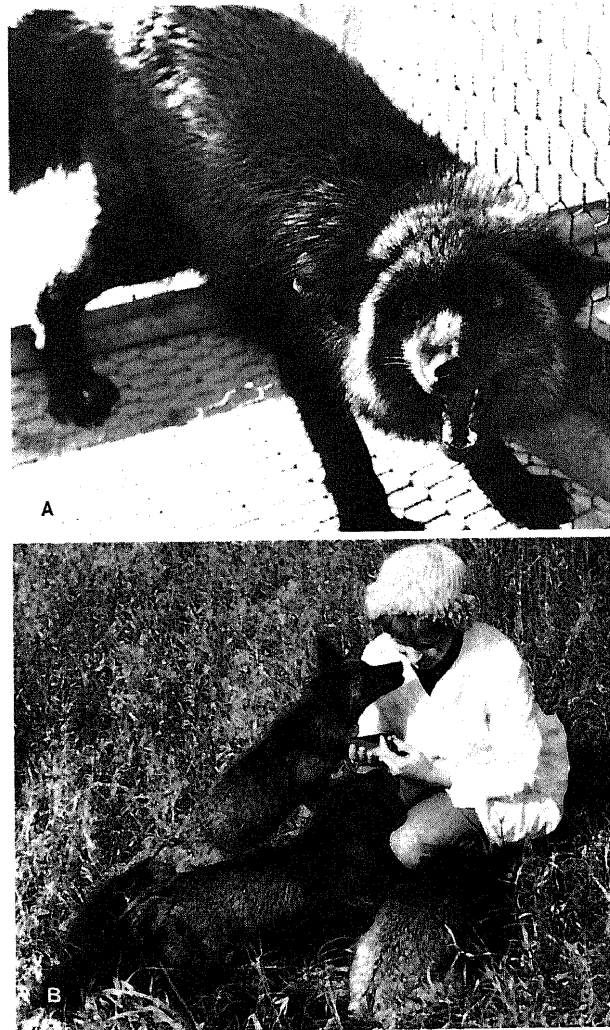


FIGURE 2—A shows a fox displaying aggressive behavior. B—tame foxes showing obvious enjoyment from human contact.

ments of emotional excitement, they even sound like dogs. There is something moving in the emotions of these foxes, that at the sight of even a strange person, they try actively to attract attention with their whining, wagging of tails, and specific movements.

The changes in behavior as a result of selection were also accompanied by changes in reproductive function of the foxes. Histological studies of vaginal smears of females born in 1962, i.e., in the fifth generation of breeding for behavior, revealed some symptoms of activation of the sexual function in the autumn (October–November); only the initial stages of proestrus were evident. However, in the foxes born in 1966–1967, a further activation of sexual function—to late proestrus—was found, while in females born in 1972–1973, even estrus was achieved in October–November. However, the males were not ready for mating at that time. The increase of extra-seasonal estral activity in tame females of a few

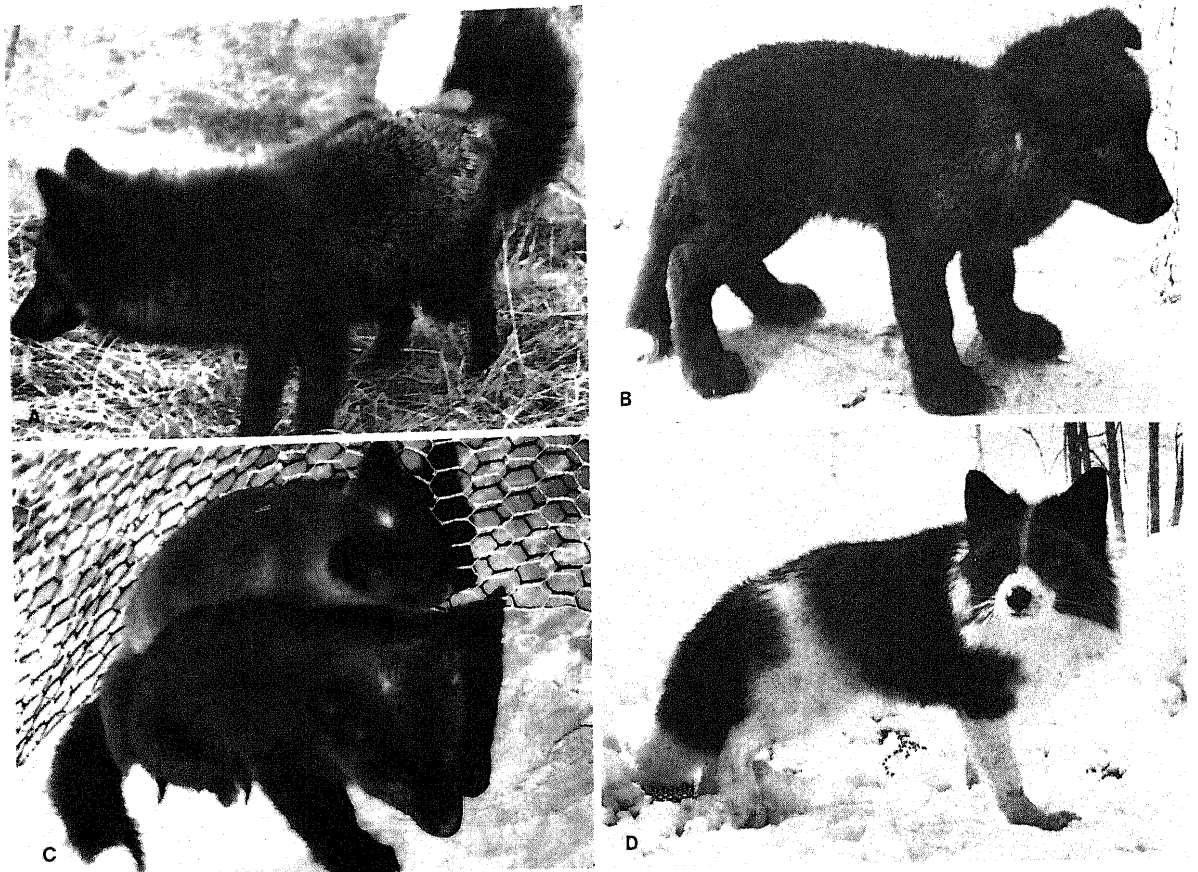


FIGURE 3—Aberrant characteristics appearing in foxes under selection for behavior. *A*—turned-up tail in dog-like

type; *B*—drooping ears; *C*—“star” piebaldness, heterozygous expression; *D*—“star” piebaldness, homozygous expression.

successive generations is presented in Figure 5. These data, as well as those given in Table I, suggest the hereditary nature of the extra-seasonal activation of reproductive function in tame females, and the possibility of increasing such reproductive behavior through selection.

The changes in reproductive function of the tame foxes

Table I. Analysis of crosses between the animals with extra-seasonal (October–November) sexual activity

Type of cross	Total no. daughters	Percentage of daughters with extra-seasonal sexual activity	Percentage of daughters without extra-seasonal sexual activity
♀♀ × ♂♂	53	32	68
♀♀ × ♂♂	34	28	72
♀♀ × ♂♂	13	15	85
♀♀ × ♂♂	35	9	91

♀♀ — females with extra-seasonal activity
 ♀♀ — females without extra-seasonal activity
 ♂♂ — males whose mothers had extra-seasonal activity
 ♂♂ — males whose mothers had no extra-seasonal activity

are also expressed in a considerable prolongation of the reproductive season. In 1976–1977, the tame females mated as early as December 20, i.e., at the shortest period of daylight. Some of these females gave birth and then mated again in March–April. Although the number of such females in our experimental population is still small, the very existence of such extra-seasonal mating is unique among foxes.

It should be noted that many females exhibiting extra-seasonal sexual function also show considerable abnormalities of reproduction during the natural breeding season. Thirty to forty percent of such females either do not reproduce during the breeding season for various reasons, or become cannibalistic and devour their offspring.

Thus, we observe an undoubted disturbance of the reproductive system, a complex of changes associated with domestication, particularly incipient di-estrousness. These changes reflect a destabilization of normal reproductive patterns that developed and were stabilized in the process of evolution.

In addition to changes in behavior and reproduction, the selection for domesticated behavior has brought about other physiological and morphological changes. The time of moulting in tame foxes is longer than in nonselected populations. Most remarkable are the changes of moulting



FIGURE 4—Foxes with brown piebaldness.

time in the females with the autumnal (October–November) activation of reproduction. In these, the moulting is first manifest in January–February, while normally moulting does not set in before April. Here, too, we are witnessing a destabilization of one of the most important adaptive responses of wild foxes.

In some of the tame foxes, even from unrelated pedigrees, quite new morphological characters appeared that are not found in wild animals but that are quite characteristic of some breeds of dogs: a peculiar position of the tail (Figure 3A), brown spots around the ears and on the neck and about the shoulder blades (Figure 4), and finally, the drooping ears characteristic of young dogs (Figure 3B). Genetic analysis has demonstrated that the mode of inheritance of these features is dominant with an incomplete penetrance and varying expression (Table II). One such trait is a peculiar piebaldness, which has appeared repeatedly in the experimental population, and which we refer to as “star”. The heterozygotes differ clearly from the homozygotes (Figure 3C and D). A similar piebaldness is often found in many breeds of domestic animals. Perhaps of great significance is the fact that some changes in the karyotype of domesticated foxes^{7,8,17,18} have also occurred.

It is well known that Vavilov explained the phenomenon of homologous variability by gene mutations within systematically close phylogenetic groups¹⁶. This plausible explanation has been confirmed by many facts, including those obtained in studies of experimental mutagenesis in

plants⁹. However, the frequency of the above mentioned aberrant phenotypes in the population selected for tame behavior is $10^{-2} - 10^{-3}$, i.e., the frequency is 2 or 3 orders

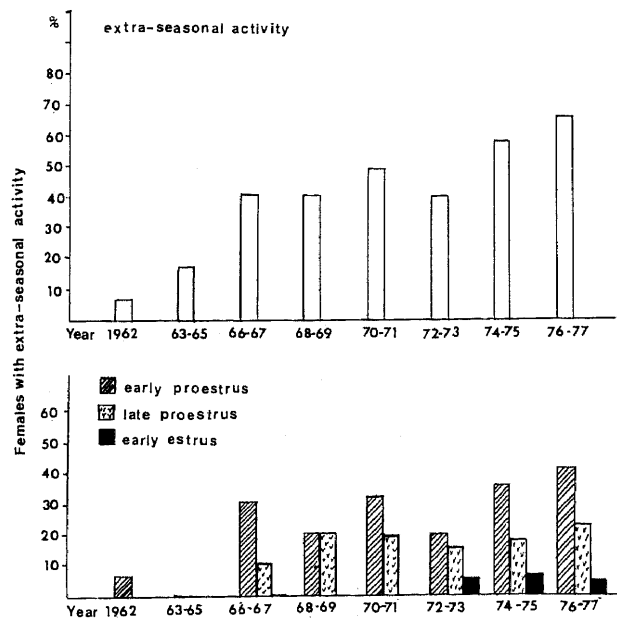


FIGURE 5—Extra-seasonal estrous activity in tame foxes born in different years.

higher than the expected frequency of spontaneous mutations. This makes us doubt that mutational changes at structural loci are the source of these aberrations. The simple mutational interpretation is contradicted by the fact that in some animals several different aberrations appear simultaneously, e.g., dog-like ears and tail and brown spots. Such simultaneity is statistically improbable if mutations at structural loci are the cause of these traits. Still more unaccountable from the point of view of mutation theory are the changes in reproduction and moulting. Our data demonstrate for foxes the kind of variability in similar characters and functions that is often observed in the domestication of other species of animals. Selection for tame domesticated behavior generates a high rate of variability, including the homologous variability described by Vavilov.

Selecting For Tame Behavior

What is peculiar and special in selecting for tame domesticated behavior? A close relationship exists between the nervous and endocrine systems. Selection for behavior can intrinsically change the hormonal status of the breed and this can also have consequences in the ontogenetic development of the animals. One should bear in mind that the neurohormonal system in all higher vertebrates, especially in mammals, plays a large role in the control of ontogeny. Hormones are important regulators of gene function with all the consequences for enzyme synthesis and biochemical activity during development.

These considerations were the basis for a series of studies comparing the hormonal system of foxes, selected and nonselected for domesticated behavior. It is impossible to describe all the results of these studies here. We did demonstrate that in males and females selected for tame behavior, the level of 11-oxycorticosteroids in the peripheral blood differs significantly from that of control, nonselected animals (Figure 6). Selection for domesticated behavior had seriously affected not only the secretory activity of the adrenals *in vitro*¹ and *in vivo*¹⁵, but also the morphology of these glands¹⁰.

All the above facts show that the selection for tame behavior has brought about important changes in the whole hypothalamic-hypophyseal-adrenal system of domesticated foxes. The selection for tame behavior has resulted also in a change of the level of steroid sex hormones, estradiol and progesterone¹². Essential is the fact that the level of the two hormones in tame females during the first days of pregnancy is higher than in the control females (Figure 7). These hormones play important roles in implantation and in embryonic mortality and may thus account for the higher fertility of tame females as compared to wild controls.

Perhaps the most important observation emerging from this series of experiments is the fact that tame females exhibit statistically significant changes in certain neurochemical characteristics in such regions of the brain as the hypothalamus, midbrain, and hippocampus¹³. The level of serotonin and its metabolite 5-hydroxyindoleacetic acid turned out to be higher in tame than in the wild females. This fact fits the type of behavior, since serotonin is known to inhibit some kinds of aggression. Moreover, serotonin plays a role in the central regulation of the hypothalamic-hypophyseal-adrenal-sexual system. Thus,

selection for tame behavior is associated with changes in both the central and the peripheral mechanisms of the neuro-endocrine control of ontogeny. These characteristics of domestication in foxes are, of course, similar to those of other animal species that were domesticated long ago. All domesticated animals were subjected to similar selection pressures at the initial stages of domestication with similar effects on ontogeny. I think that these observations explain well the appearance of homologous variations in the system of reproduction and moulting in domesticated foxes and other domesticated animals.

The evolutionary significance of this phenomenon of homologous variation is much less clear. A role for gene activation or inactivation in the process of evolution has been proposed by various authors^{11,19} but there is still no firm evidence for such processes, and the entire problem of gene regulation still awaits solution.

In this connection, the mode of inheritance of "star" piebaldness is of some interest. Segregation analyses of crosses between homozygotes for this gene have clearly demonstrated a deficiency of homozygotes in the progeny, although the 3:1 ratio was fulfilled. The data show that this fact cannot be accounted for by embryonic mortality of the homozygotes. Evidently, in a fraction of the homozygotes one of the two homologous mutant genes determining piebaldness is functionally inactive ("dormant"), which makes genetically homozygous animals look like heterozygotes.

One can imagine that under the influence of an altered hormonal equilibrium a number of "dormant" genes could be expressed, resulting in a high frequency of appearance of a whole complex of morphological characters (position of the tail, ears, etc.) mentioned above.

Table II. The pattern of segregation in progeny of heterogeneous and homogeneous crosses of aberrant animals

Parents ♀	×	♂	Total no. offspring	Normal (%)	Aberrant (%)
normal		hanging ears	66	86.4	13.6
hanging ears		normal	28	89.3	10.7
Total			94	87.2	12.8
hanging ears		hanging ears	27	51.9	48.1
normal		brown piebald	14	100	—
brown piebald		normal	73	91.8	8.2
Total			87	93.1	6.9
brown piebald		brown piebald	24	50.0	50.0
normal		turned-up tail	189	82.0	18.0
turned-up tail		normal	52	80.8	19.2
Total			241	81.7	18.3
turned-up tail		turned-up tail	61	78.7	21.3

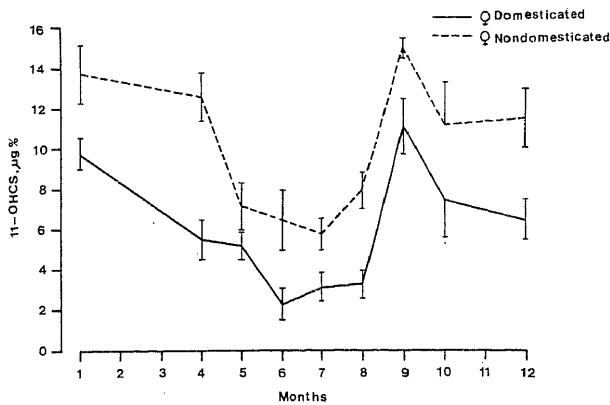


FIGURE 6—Seasonal dynamics of 11-OHCS in tame and control foxes.

It is impossible, of course, to deny the contribution of mutations to the phenomenon of homologous variability. Basic genetic mechanisms, including gene drift with all its consequences, also play an important role in the increase of variation under domestication. However, the key to domestication and to homologous variation in animals seems to be the selection for behavioral traits that are associated with or lead to many other phenotypic changes.

Darwinian, Stabilizing, and Destabilizing Selection

What is the nature and the essence of the selection that serves as the driving force of domestication? What is the form, or rather the effect, of this selection? The modern literature on evolutionary genetics knows many forms of selection. After Darwin, who distinguished natural and artificial selection by a formal criterion, a series of authors have described other forms of selection (conserving, disruptive, etc.). Schmalhausen¹⁴ distinguished two main modes of selection: promoting selection (the main force of evolution as argued by Darwin); and stabilizing selection, the theory of which was formulated by Schmalhausen himself.

Darwinian selection is based mainly on mutations of minor effect that lead to a very slow shift of the average adaptedness of populations and species to the conditions of new ecological niches within a given environment. As Darwin wrote, these selection processes do not generate any new variation, but use only what already exists. Modern population genetics and the dominant theory of evolution are based on this type of selection. Stabilizing selection operates under conditions of a relatively stable environment to which the species is well adapted. It provides for stabilization of ontogeny to develop the optimum phenotype for the given environment. Stabilizing selection displays its effect through the elimination of mutations disturbing the normal ontogeny and phenotype. It maintains variation within the optimum limits developed by evolution, but does not create new variations. However, all modes of selection result in discarding the unfit. This was well understood by Schmalhausen, the second (posthumous) edition of whose "Factors of Evolution" ended as follows: "In conclusion I want to point

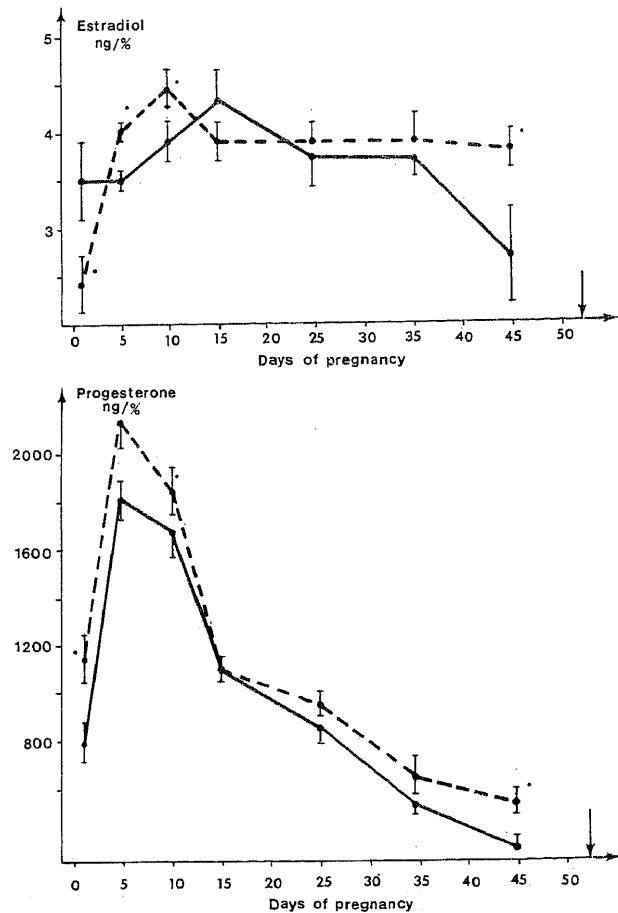


FIGURE 7—Variations in estradiol and progesterone levels during pregnancy in tame and control animals.

out that the stabilizing selection in its concrete manifestation is not a special form of selection. It would be more correct to speak of promoting and stabilizing *effects* (italics added) of the general process of natural selection."

However, selection for tame behavior seems to result in breaking up previously integrated ontogenetic systems and thus leads to multiple phenotypic effects that seem genetically unrelated to the selected character, namely tame behavior. In a genetic and biochemical sense, what may be selected for are changes in the regulation of genes—that is, in the timing and the amount of gene expression rather than changes in individual structural genes. Selection having such an effect is called by me *destabilizing selection*²⁻⁴. The selection becomes destabilizing when it affects, directly or indirectly, the systems of neuroendocrine control of ontogenesis. This seems always to be the case when some new stressful factors appear in the environment, or when stresses usual for the species increase in strength. One may think therefore that stress is one of the important factors accelerating the evolution of life, especially at the highest level of organization where neuro-hormonal controls on ontogeny are most effective. Destabilizing selection²⁻⁴ could break up normal

patterns of gene activation and inhibition and result in a great increase in the range and rate of hereditary variation, which again is subject to specific selective forces. The process of domestication in all animal species seems to have resulted in the same kinds of homologous variations as a result of selection for the single important characteristic of tame behavior. Foxes are only the latest animals to be added to this list of domesticated species. The destabilizing effects of domestication can also lead to many undesirable characteristics, but further selection tends to eliminate or modify these characters. The biological principles of selection can also, of course, apply to human beings. During our evolution we have not escaped from the stressful conditions under which destabilizing selection may operate. The objective dialectics of life consist in a contradictory unity of good and evil and we must see clearly this simple yet indisputable truth when attempting to estimate the prospects of evolution of life on our beautiful planet.

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