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Experimental Hybridization and an Evaluation of the Fertility of Some Forms of the House Mouse Supraspecies Complex *Mus musculus* (Rodentia, Muridae)

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Abstract—The degree of development of the mechanisms of postcopulatory isolation was evaluated on the basis of experimental hybridization of representatives of three subspecies of *M. musculus* (*M. m. musculus, M. m. wagneri,* and *M. m. gansuensis*) and remote populations of the subspecies *M. m. musculus*. Experimental crosses between the different subspecies and populations indicated the presence of initial stages of postcopulatory reproductive isolation between some forms of house mice. In a number of crosses conducted between different populations and subspecies of *M. musculus*, asymmetry was observed. In one variant of mating, *M. m. musculus* (male) × *M. m. wagneri* (female), a reduced intensity of breeding and nonviability of pups were observed. A decrease in the intensity of reproduction was found in all variants of crosses that used male *M. m. musculus* from the city of Ishim. These data are assumed to confirm the previous assumption about the hybrid origin of mice inhabiting that city. The results confirm a significant level of divergence of the subspecies *M. m. musculus* and *M. m. wagneri*. Thus, initial stages both of post- and precopulatory isolation mechanisms between *M. m. wagneri* and *M. m. musculus* were shown.

Keywords: Mus m. musculus, *M. m. wagneri*, *M. m. gansuensis*, experimental hybridization, subspecies, initial stages of divergence

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INTRODUCTION

According to the concept of biological species, speciation is based on the formation of reproductive isolation between closely related forms. Some researchers believe that the study of the genetic basis of this process is the key to understanding speciation (Coyne and Orr, 1998; Turelli et al., 2001; Wu, 2001). To explain the evolutionary processes associated with the formation of the mechanisms of reproductive isolation (both pre- and postcopulatory) in closely related taxa, it is necessary to analyze their functioning in forms at different stages of divergence—in the reliably isolated sympatric species, in the parapatric forms crossing in contact zones, and in the allopatric species and populations of the same species. Over the past few decades, house mice of the supraspecies complex *Mus musculus* s. l. have served as a model group to study various aspects of evolution, including the formation of isolating mechanisms (Sage et al., 1993; Kotenkova and Naidenko, 1999; Kotenkova, 2000, 2002, 2014; Kotenkova and Ambaryan, 2003; Berry and Scriven, 2005; Ambaryan et al., 2010). The systematics of house mice at the species level has been repeatedly discussed by us and other researchers (Sage et al., 1993; Bonhomme et al., 1994; Mezhzherin, 1994; Kotenkova, 2000; Tucker, 2008). This gives us reason to share the view of the species taxonomic status of *Mus musculus* (L. 1758) and the subspecies status of *M. m. musculus, M. m. wagneri,* and *M. m. gansuensis.*

Experimental hybridization has conventionally been used, and it currently used to evaluate the degree of development of the postcopulatory isolation mechanisms between closely related forms of mammals and to refine the level of divergence and taxonomic status of these forms (Meyer et al., 1981, 1996; Malygin, 1983; Britton-Davidian et al., 2005; Koval'skaya et al., 2014). This method was used to investigate the postzygotic isolating mechanisms between sympatric closely related species of house mice, which were analyzed in a number of studies by Russian (Bulatova et al., 1986; Lavrenchenko et al., 1989, 1994) and foreign (Biddle et al., 1994; Forejt, 1996; Elliott et al., 2001; Britton-Davidian et al., 2005) researchers. It should be noted that the structure of the chromosome set in the house mice of the supraspecies complex *Mus musculus* s. l. is fairly well preserved in terms of both external morphology of chromosomes and their number ($2n = 40$) (Bulatova, 1994). The exception is *Mus domesticus* (Rutty 1772): a broad "Robertsonian fan," which is characterized by the presence of a number of chromosome races with different numbers of chromosomes and was described in this species (Capanna et al., 1976). As was shown by the results of experimental hybridological analysis, all species of house mice are crossed in the laboratory. The disturbances observed in hybrids and backcrosses are quite diverse: asymmetry in the sex ratio in F_1 hybrids, male sterility and reduced female fertility, and meiotic abnormalities in male hybrids and backcrosses (Bulatova et al., 1986; Lavrenchenko et al., 1989, 1994). Data regarding the degree of development of the postzygotic isolating mechanisms of house mice at the early stages of divergence are scanty; all of them boil down to the results of crosses, evaluation of fertility, and study of mechanisms of sterility in natural hybrids from the European hybridization zone and/or experimental hybrids *M. musculus* × *M. domesticus,* often with the use of strain mice (Forejt and Ivanyi, 1974; Alibert et al., 1997; Britton-Davidian et al., 2005; Good et al., 2008; White et al., 2011; Forejt et al., 2012; Turner et al., 2012; Bhattacharyya et al., 2013). In our study, we evaluated the degree of development of the postcopulatory isolation mechanisms in the forms of house mice at the early stages of divergence—in subspecies and in remote populations. The subspecies taxonomy of *Mus musculus* is discussed in a number of studies by Russian and foreign authors (Lavrenchenko, 1990; Lavrenchenko et al., 1994; Yakimenko et al., 2003; Yonekawa et al., 2003; Korobitsina and Yakimenko, 2004; Spiridonova et al., 2008a, 2008b) and remains poorly developed. Modern authors identify three to seven subspecies, of which the following morphological and/or cytogenetically diagnosed subspecies were used in this work: *Mus musculus musculus* Linnaeus 1758 (syn. *borealis, funereus, germanicus, gilvus, hanuma, hapsaliensis, heroldi, hortulanus, polonicus, tomensis, variabilis,* and *vinogradovi*); *M. m. wagneri* Eversmann 1848 (syn. *bicolor, decolor, gansuensis, nogaiorum, oxyrrhinus, pachycercus, sareptanicus,* and *sewertzowi*), and *M. m. gansuensis* Satunin 1903 (=*raddei*, Kastschenko 1910). The synonyms for *M. m. musculus* and *M. m. wagneri* are given according to Marshall (1998), and for *M. m. gansuensis,* according to Korobitsina and Yakimenko (2004), because Marshall (1998) narrowed *gansuensis* to the synonyms *wagneri,* which does not correspond to the modern notion (Yakimenko et al., 2000; Korobitsina and Yakimenko, 2004).

The lifestyle of subspecies is different. Representatives of *M. m. musculus* in the major part of the range live in human buildings; however, they can leave them and move to open habitats in the warm season of the year (Tupikova, 1947; Sokolov et al., 1990). *M. m. wagneri* and *M. m. gansuensis* are subspecies spread in south parts of *Mus musculus* species range. Representatives of these subspecies in a considerable part of the range inhabit open biotopes all year round but can also populate human buildings (Vinogradov et al., 1936; Sludskii et al., 1977); i.e., they are facultative synanthropes. Morphologically, *M. m. wagneri* and *M. m. gansuensis* differ from *M. m. musculus* in color and tail length but do not differ between themselves. Their tail is relatively shorter than that of *musculus;* the color of the back, in contrast to *musculus,* is light, and the belly is very light, sometimes white (Yakimenko et al., 2003; Korobitsina and Yakimenko, 2004). All subspecies are reliably distinguished karyologically. The exoanthropic mice that phenotypically correspond to the subspecies *M. m. wagneri* are characterized by low levels of heterochromatin and its uniform distribution. Their X chromosome is of the "*musculus* type," chromosomes 0–4 are devoid of heterochromatin, and chromosome 3 sometimes contains C-blocks (Yakimenko et al., 2003; Korobitsina and Yakimenko, 2004). Representatives of another subspecies, *M. m. gansuensis,* externally indistinguishable from *M. m. wagneri,* which were distinguished by Yakymenko et al. (2003), are characterized by the presence of marker autosomes (17 and 18, sometimes 15 and 19) carrying large C-blocks. Thus, the karyological method makes it possible to discriminate reliably between subspecies, whereas neither the allozyme analysis nor mtDNA studies reveal differences between them. According to the allozyme analysis, subspecies *M. m. musculus* and *M. m. wagneri* have no diagnostic loci, and genetic differentiation between them is negligible (Mezhzherin and Kotenkova, 1989, 1992; Milishnikov, 1994). In addition, according to data obtained by us (Maltsev, 2011, 2011a; Maltsev and Bazhenov, 2013) and other researchers (Yonekawa et al., 2003), studies of the control mtDNA region showed no genetic divergence between *M. m. musculus* and *M. m. wagneri*. However, the results of RAPD PCR analysis not only confirm the isolation of these taxa but also testify to their strong molecular genetic differentiation (Spiridonova et al., 2008). The level of genetic distances between *M. m. wagneri* and other subspecies is significantly greater than that between the "good" sympatric species *M. musculus*–*M. spicilegus* and the allopatric species *M. musculus*–*M. macedonicus*. This fact allowed the authors to propose raising the status of *M. m. wagneri* to the species (Spiridonova et al., 2008). It was also shown that the stereotype of exploratory behavior of *M. m. wagneri* substantially differs from that of *M. m. musculus* and resembles the exploratory behavior of the free-living species of house mice (Sokolov et al., 1993; Kotenkova et al., 1994, 2003). According to Yakimenko et al. (2003), the range of the subspecies *M. m. wagneri* covers a vast area of the steppe and semidesert zone, located between the Lower Volga region in the west and the Zaisan Basin and the Altai Mountains in the east. The western boundary may reach the Crimea and Voronezh region.

It is necessary to differentiate the ranges of *M. m. wagneri* and *M. m. gansuensis* in the east and the ranges of *M. m. wagneri, M. d. bactrianus,* and *M. d. praetextus* in Transcaucasia and Central Asia. In the west and north of Kazakhstan, the hybridization of *M. m. wagneri* and *M. m. musculus* is assumed. The authors suggest the existence of at least one more subspecies of "*wagneri*-like" house mice, representatives of which occur in Manchuria (northeast China) and South Korea. They differ from *M. m. gansuensis* by the dark brown color of the back (Tsuchiya et al., 1994). This subspecies has marker chromosome 18 with a characteristic distribution of heterochromatin C-blocks (Moriwaki et al., 1986). The subspecies name of this form needs to be clarified. On the basis of the results of karyological analysis, the "*wagneri*-like" short-tailed white-bellied house mice should be divided into three or four separate subspecies. It was suggested that the "*wagneri*-like" subspecies should be classified into an separate group, along with such taxa as *M. domesticus, M. musculus*, and *M. castaneus* (Waterhouse, 1842) (Yakimenko et al., 2003; Korobitsina and Yakimenko, 2004). However, on the basis of the above-mentioned results of RAPD PCR analysis, this assumption is called into question because of the marked isolation of the subspecies *M. m. wagneri* and the considerable molecular genetic differentiation of *M. m. wagneri* and *M. m. gansuensis* (Spiridonova et al., 2008). The results of experimental crosses performed by us provide additional information for evaluating the taxonomic status of these subspecies.

The aim of our studies was to evaluate the degree of development of the mechanisms of postcopulatory isolation between the taxa of the supraspecies complex *Mus musculus* s. l. at different stages of divergence. The objective of this work was analysis of this problem on the basis of the results of experimental hybridization of representatives of *M. musculus* subspecies and remote populations of the subspecies *M. m. musculus.*

MATERIALS AND METHODS

Experimental crosses between different forms of house mice were performed in the vivarium at the Chernogolovka scientific experimental station of Severtsov Institute of Ecology and Evolution in 2010–2014. The species and subspecies identification of mice was determined on the basis of morphological traits and the sites of their capture (i.e., the taxon within the range of which a given animal was caught was taken into account). Earlier, the phylogenetic relationships between the haplotypes of mice used in this study as well as other specimens from the same samples were evaluated on the basis of polymorphism of the hypervariable region of the control mtDNA region (D-loop) (Maltsev, 2011a, 2011b). It was shown that, on the phylogenetic tree built by the neighbor joining (NJ) method, all haplotypes were separated from the outer group (*M. domesticus*) with a high bootstrap support (100%). This fact indicates that they have the mtDNA of *M. musculus* and is suggestive of the genetic unity of different forms of *M. musculus* (Maltsev, 2011; Maltsev and Bazhenov, 2013).

In this study, we used the animals of the F_1, F_2, and F_3 generations derived from the animals caught in the wild. *M. m. musculus* were caught in Moscow, Moscow oblast, Ishim, Chisinau, and Tsimlyansk sands (Volgograd region). *M. m. wagneri* were caught in the vicinity of Astrakhan, and *M. m. gansuensis* were caught in the village of Nizhnii Tsasuchei (Transbaikalia). Pairs of house mice (male and female) were formed from mature (40–90 days old) animals for 3–6 months. During this time, the number of litters obtained and pups born was counted, and the viability of pups was evaluated for 40 days after birth. Additionally, the ratio of the pairs that produced progeny to the total number of pairs formed was determined. For convenience, a group of house mice caught in a particular area will be conditionally called a "population," and the crosses between them will be called intrapopulational. To evaluate the breeding intensity of subspecies and remote populations of *M. musculus*, we performed four series of crosses in different versions (Tables 1–4). In the first control series, we evaluated fertility in the pairs consisting of representatives of one subspecies or population (Table 1). In total, 108 pairs from the representatives of six populations of *M. musculus* were formed. In the second series, to detect the presence or absence of restrictions on the breeding between subspecies, ten variants of crosses between six populations of *M. musculus* were performed, and 67 pairs were formed (Table 2). In the third series, the characteristics of breeding intensity in the pairs consisting of mice from remote populations of the subspecies *M. m. musculus* were evaluated. In total, 21 pairs from the representatives of three populations were formed (Table 3). In the fourth series, to evaluate the fertility of male F_1 hybrids, five types of backcrosses in different variants were performed and 19 pairs were formed (Table 4).

The fertility of hybrid males was also evaluated by determining the sperm concentration and by analyzing the sperm morphology (Tables 2, 3). The sperm concentration was evaluated by the method described earlier (Kotenkova and Osadchuk, 2009).

The animals were housed under standard conditions with natural illumination. The mice received a fodder consisting of oats with an admixture of sunflower as well as carrot. Data were processed statistically using the Mann–Whitney *U* test for two independent samples when comparing the number of pups per litter and the chi-square test for comparing 2 × 2 the number of litters × the number of pups (since the differences for this parameter were nonsignificant, these data are not shown in this article). Statistical calculations were performed using the STATISTICA 7.0 software. The number of pups per litter was compared

Table 1. Characteristics of the intensity of the breeding house mice *M. musculus* in intra- and interpopulation crosses

Subspecies and/or population	Number of pairs			Total number of litters	Total number of pups	Number of litters per breeding female per month, *X* (max–min)	Number of pups per litter, *X* (max–min)	Number of pups per breeding female per month, *X* (max–min)	Pup mortality before 20 days old, %	Interval between litters, days, *X* (max–min)
	total	bred								
		number	%							
M. m. musculus (M)	19	15	78.9	37	182	0.6 (0.3–1.0)	4.9 (3–8)	2.8 (1.1–4.2)	2.6%	58.6
M. m. musculus (I)	15	8	53.3	13	56	0.4 (0.2–0.8)	4.3 (3–6)	2.0 (0.9–3.2)	26.3%	62.0
M. m. musculus (C)	3	3	100	7	23	0.6 (0.3–0.8)	3.3 (1–6)	2.7 (1–4.4)	13%	43.0
M. m. musculus (Ts)	10	10	100	18	69	0.6 (0.1–1.0)	3.8 (2–7)	2.3 (1.3–3.5)	4.5	56.0
M. m. wagneri	23	21	91.3	31	135	0.4 (0.1–0.7)	4.3 (1–8)	2.1 (0.8–3.0)	8.9	61.4
M. m. gansuensis	38	26	68.4	36	146	0.4 (0.3–1.0)	4.05 (1–7)	2.2 (1.0–3.7)	4.8	64.8

Designations: M—Moscow and Moscow region, I—Ishim, C—Chisinau, Ts—Tsimlyansk Sands. For all tables: *X*—mean value, max–min—minimum and maximum values.

only in those cases where the number of litters was at least six (Table 5).

RESULTS

In the intrapopulational crosses of *M. m. musculus,* the lowest breeding indices were recorded for the house mice from Ishim. Of the 15 pairs formed, only 8 gave progeny (Table 1), which accounted for 53%, whereas in the pairs of mice from other sites, this value was 78.9% (Moscow and Moscow region) and 100% (Chisinau, Tsimlyansk sands). In the pairs formed by mice from Ishim, a high mortality of pups during feeding was detected. Among other indices characterizing the intensity of breeding, it is necessary to mention the mean number of pups per litter. The lowest value of this index (3.3) was detected in *M. m. musculus* from Chisinau, and the highest value (4.9) was in *M. m. musculus* from Moscow and Moscow region (Table 1). Each pair from Moscow and Moscow region produced at least two litters. Mice from Chisinau showed a high mortality of pups during weaning. The breeding indices of the representatives of facultatively synanthropic subspecies *M. m. wagneri* and *M. m. gansuensis* did not differ significantly from the indices of the synanthropic forms of house mice (Tables 1, 5).

In the crosses between the subspecies *M. m. musculus* (Moscow and Moscow region) and *M. m. wagneri,* progeny was produced by only some pairs (Table 2). In the cross variant between male *M. m. musculus* and female *M. m. wagneri,* only two pairs gave progeny, whereas in another variant (male *M. m. wagneri* and female *M. m. musculus*), all pairs formed bred successfully. In this cross variant, the number of pups per litter differed significantly from that for the pairs consisting of *M. m. musculus* from Moscow (Table 5); in other cross variants, differences were nonsignificant (Table 5). The number of pups per litter was significantly higher in the hybrid pairs of the two subspecies as compared to the parental subspecies. We assumed that this may be due to the higher sperm quality of male *M. m. wagneri* compared to male *M. m. musculus* (Ambaryan et al., 2015). It should be noted that, in the first variant, pups obtained from two breeding pairs rarely survived. Pups from one litter died at an age of 5–15 days. Pups produced by another pair, which gave two litters, survived in part. Both hybrid females and hybrid males were fertile (Table 2). In the backcrosses of F_1 hybrid females with males of parental forms, no significant changes in the breeding intensity were observed, and the progeny produced (both females and males) were viable, although in one variant of crosses a slight increase in pup mortality during weaning was detected (Table 4). All pairs formed by male *M. m. wagneri* and female *M. m. musculus* from Tsimlyansk sands bred and produced viable progeny (Table 2).

For experimental hybridization of representatives of *M. m. gansuensis* and *M. m. musculus,* we used the individuals from Ishim. They were chosen as the most geographically close populations of the subspecies *M. m. musculus* to the range of the subspecies *M. m. gansuensis*. In the variant of cross of female *M. m. gansuensis* and male *M. m. musculus* from Ishim, the proportion of breeding pairs was very low and accounted for 28.6%. The progeny was nonviable, the majority of pups did not live to 15 days, and the remaining pups died before the onset of maturity (Table 2). Conversely, in the variant of cross of male *M. m. gansuensis* and female *M. m. musculus,* the breeding pairs accounted for 62.5%; however, the mortality of pups during feeding was relatively high and reached 43%. Two males studied were fertile (Table 2). In the experimental hybridization of *M. m. gansuensis* and *M. m. musculus* from Moscow and Moscow region, a significant decrease in the breeding intensity was also observed in one of the variants of crosses. Out

Table 2. Characteristics of the intensity of the breeding house mouse subspecies hybridization *M. musculus*

Variants of crosses	Number of pairs			Total number of litters	Total number of pups	Mean number of litters per breeding female per month	Mean number of pups per litter	Mean number of pups per breeding female per month	Pup mortality before 20 days old, %	Mean interval between litters, days	Generative state of progeny	Number of hybrids analyzed for fertility
	total	bred										
		number	%									
♂*M. m. w.* ♀*M. m. m.* (M)	10	10	100	22	110	0.7 (0.5–1.0)	50	3.5 (0.5–1.0)	16.6	39.8	♀, ♂ fertile	8 ♂♂ (SA) 11 ♀♀ (HA)
♂*M. m. m.* (M) ♀*M. m. w.*	11	2	18.2	3	10	0.5 (0.5–0.5)	3.3	1.7 (1.5–2.0)	60.0	65.0	–	–
♂*M. m. w.* ♀*M. m. m.* (Ts)	6	6	100	11	36	0.7 (0.4–1.0)	3.3	2.2 (0.9–3.5)	0.0	37.3	–	–
♂*M. m. g.* ♀*M. m. m.* (I)	8	5	62.5	5	14	0.5 (0.3–0.7)	2.8	2.0 (1.5–2.5)	43.0	49.5	♂ fertile	2 ♂♂ (SA)
♂*M. m. m.* (I) ♀*M. m. g.*	7	2	28.5	2	8	0.5 (0.4–0.7)	4.0	1.8 (1.5–2.0)	87.5	50.1	–	–
♂*M. m. g.* ♀*M. m. m.* (M)	7	6	86	10	50	0.6 (0.5–1.0)	50	2.9 (0.9–6.5)	8.0	34.42	–	–
♂*M. m. m.* (M) ♀*M. m. g.*	7	1	14.3	2	8	0.4 (0.4–0.4)	4.0	0.5 (0.5–0.5)	12.5	32.5	–	–
♂*M. m. g.* ♀*M. m. w.*	5	1	20	2	8	0.3 (0.3–0.3)	4.0	1.3 (1.3–1.3)	25.0	37.5	–	–
♂*M. m. w.* ♀*M. m. g.*	6	4	66	7	36	0.7 (0.5–1.0)	5.1	3.3 (2.5–5.0)	0	33.25	–	–

Designations: *M. m. m.—Mus musculus musculus, M. m. w.—Mus musculus wagneri, M. m. g.—Mus musculus gansuensis,* "–"—no data; SA—sperm analysis, HA—hybridological analysis. See also Table 1.

Table 3. Characteristics of the intensity of the breeding house mice hybridization of remotely distant populations *M. m. musculus*

Cross variant	Number of pairs			Total number of litters	Total number of pups	Mean number of litters per breeding female per month	Mean number of pups per litter	Mean number of pups per breeding female per month	Pup mortality before 20 days old, %	Generative state of progeny	Number of hybrids analyzed for fertility
	total	bred									
		num-ber	%								
♂*M. m. m.* (M) ♀*M. m. m.* (I)	4	2	50.0	2	7	0.5 (0.4–0.6)	3.5	1.8 (1.5–2.0)	0.0	♀, ♂ fertile	1 ♂ (AU), 2 ♀♀ (GA)
♂*M. m. m.* (I) ♀*M. m. m.* (M)	4	0	0	0	0	–	0.0	–	–	–	–
♂*M. m. m.* (M) ♀*M. m. m.* (C)	6	2	33.3	2	8	0.5 (0.4–0.6)	4.0	20	40.0	–	–
♂*M. m. m.* (C) ♀*M. m. m.* (M)	7	4	57.1	10	28	0.5 (0.4–0.7)	2.8	2.5 (2.0–3.0)	0.0	♀, ♂ fertile	2 ♂♂ (GA), 4 ♀♀ (GA)

For designations, see Tables 1 and 2.

Table 4. Characteristics of the breeding intensity of house mice in backcrossing

Cross variant	Number of pairs			Total number of litters	Total numbe of pups	Mean number of litters per breeding female per month	Mean number of pups per litter	Mean number of pups per breeding female per month	Pup mortality before 20 days old, %	Mean interval between litters, days
	total	bred								
		num-ber	%							
♂ *M. m. m.* (M) ♀ F_1 (♂ *M. m. w.* × ♀ *M. m. m.* (M)	6	4	66.7	4	13	0.5 (0.4–0.6)	3.3	2.2 (1.0–3.0)	33	48.0
♂ *M. m. w.* ♀ F_1 (♂ *M. m. w.* × ♀ *M. m. m.* (M)	5	4	80.0	4	16	0.8 (0.5–1.0)	4.0	3.5 (1.5–4.5)	0	– *
♂ *M. m. m.* (M) ♀ F_1 (♂ *M. m. m.*(M) × ♀ *M. m. m.* (I)	2	2	100	2	5	0.5 (0.4–0.7)	2.5	1.3 (1.0–1.5)	20	– *
♂ *M. m. m.* (M) ♀ F_1 (♂ *M. m. m.* (C) × (♀ *M. m. m.* (M)	4	4	100	9	43	0.6 (0.5–0.8)	4.7	3.2 (2.8–4.0)	17.5	65.4
♂ F_1 (♂ *M. m. m.* (C) × ♀ *M. m. m.* (M) ♀ *M. m. m.* (M)	2	2	100	4	16	0.6 (0.5–0.6)	4.0	2.0 (1.5–2.6)	11.7	–

For designations, see Tables 1, 2.

of seven pairs formed by males from Moscow and Moscow region and female *M. m. gansuensis,* progeny was produced by only one pair. In the case of cross of *M. m. wagneri* and *M. m. gansuensis,* the breeding intensity decreased compared to the parental forms. In the variant of cross of male *M. m. gansuensis* × female *M. m. wagneri,* only one of five pairs formed produced pups, whose mortality was fairly high (Table 2). However, these experiments should be continued.

The results of experimental hybridization of *M. m. musculus* from remote populations are shown in Table 3. The variant of crosses of male *M. m. musculus*

Table 5. Evaluation of the significance of differences in the number of pups per litter according to the Mann–Whitney *U* test

Compared variants of crosses	*U*	Z	P
M. m. m. *M. m. w.*	14.50	0.93	0.31
M. m. w. *M. m. g.*	16.50	–0.64	0.49
M. m. m. *M. m. g.*	15.00	1.01	0.30
♂ *M. m. w.* × ♀ *M. m. m.* (M) *M. m. m.* (M)	0.00	–2.00	0.04
♂*M. m. w.* × ♀ *M. m. m.* (M) *M. m. w.*	14.00	0.18	0.84
♂ *M. m. g.* × ♀ *M. m. m.* (M) *M. m. m.* (M)	4.00	0.00	1.00
♂ *M. m. g.* × ♀ *M. m. m.* (M) *M .m. g.*	1.00	–1.55	0.09
♂ *M. m. w.* × ♀ *M. m. g.* *M. m. w.*	2.00	0.58	0.54
♂ *M. m. w.* × ♀ *M. m. g.* *M. m. g.*	3.50	–0.58	0.54
♀ *M. m. m.* (C) × ♂ *M. m. m.* (M) *M. m. m* (M)	1.00	1.15	0.20
♀ *M. m. m.* (C) × ♂ *M. m. m.* (M) *M. m. m* (C)	0.00	–1.73	0.08
♂ *M. m. m.* (M) × ♀ F_1 (♀ *M. m. m.* (M) × ♂ *M. m. m.* (C) *M. m. m.* (M)	3.00	–0.46	0.62

For designations, see Tables 1, 2.

(Ishim) × female *M. m. musculus* (Moscow and Moscow region) gave no progeny, whereas in another variant of crosses (female *M. m. musculus* (Ishim) × male *M. m. musculus* (Moscow and Moscow region)) two pairs bred. The crosses of house mice from Moscow and Moscow region and Chisinau showed a slight decrease in the number of breeding pairs compared to the control intrapopulational crosses. However, since the number of breeding pairs put together was small, this decrease cannot be postulated confidently. All studied hybrid males and females proved to be fertile. In the backcross of hybrids with the individuals of the parental forms, relatively high indices of breeding intensity were obtained.

DISCUSSION

Before discussing the results of crosses, it should be noted that sexual isolation is often asymmetrical (i.e., there is a certain reproductive isolation between closely related species and populations of the same species, but it manifests itself only in crosses in one direction). This phenomenon is widespread in the genus *Drosophila* (Watanabe and Kawanishi, 1979; Kaneshiro, 1980; Coyne and Orr, 1989), is observed in salamanders (Arnold et al., 1996), and was also found in other groups of animals (Soyne and Orr, 1998, 2004). Arnold et al. (1996) assumed that the asymmetry of crosses is a temporary phenomenon that is rapidly lost in the course of divergence of populations. After the completion of divergence and the formation of reproductive isolation between forms (i.e., as a result of speciation), the asymmetry should eventually disappear. If the asymmetry is widespread within a certain taxonomic group of organisms, it testifies to the influence of sexual selection, which contributes to speciation (Soyne and Orr, 1998).

In our experiments, asymmetry was observed in the number of crosses performed both between representatives of different subspecies and between spatially remote populations of *M. musculus*. It was especially well expressed in the crosses of *M. m. musculus* and *M. m. wagneri,* since the pairs formed by male *M. m. musculus* and females *M. m. wagneri* either did not breed or produced progeny with reduced viability. F_1 hybrid males obtained from another variant of crosses were viable and fertile. These data indicate the beginning of development of the postcopulatory mechanisms of isolation between *M. m. musculus* and *M. m. wagneri* and support the concept of both a significant divergence of these subspecies and the effects of sexual selection, which promotes speciation. This is also confirmed by our recent studies, according to which representatives of *M. m. musculus* and *M. m. wagneri* distinguish individuals of their subspecies from those (individuals) of the other subspecies by the odour of urine (Maltsev and Kotenkova 2013). These data testify to the development of not only postcopulatory but also precopulatory mechanisms of isolation between subspecies (Kotenkova, 2014). Taking into account the data discussed in the Introduction, a substantial divergence of *M. m. musculus* and *M. m. wagneri* can be postulated with a high degree of certainty*,* although it has not yet reached the species level.

The results of studies may also indicate the existence of restrictions on the hybridization between *M. m. musculus* and *M. m. gansuensis,* as in the case of the two subspecies discussed above. However, data obtained by crossing *M. m. musculus* from Ishim with different forms of house mice indicate another possible cause that could affect the success of crosses—the low fertility of male house mice from Ishim. The breeding intensity in all pairs formed by the house mice from Ishim was significantly lower than that in the pairs from other places. Importantly, in all interpopulation crosses in which the males from Ishim were used, the hybrids produced by such pairs had a reduced viability: the majority of them did not live to 20 days. However, the combinations in which females from Ishim were crossed with males form other populations gave viable hybrids. Earlier, on the basis of the results of morphological analysis, we assumed a hybrid origin of house mice from Ishim (Maltsev, 2009, 2011). If the assumption about their hybrid origin is true, then the higher fertility of females is consistent with Haldane's rule (Haldane, 1922). Hybridization leads to oppression of hybrids of the heterogametic sex. For the taxa with heterogametic males, including mammals and some insects (in particular, representatives of the genus *Drosophila*), this usually affects the X-autosomal interactions (Turrelli and Orr, 1995). F_1 and F_2 hybrid males are often characterized by a reduced fertility and sometimes sterility, nonviability, disturbed spermatogenesis, underdeveloped testes, and low sperm quality. Possibly, the absence of progeny in the vast majority of pairs including the males from Ishim could be caused by their sterility or reduced fertility. However, in the crosses of female *M. m. gansuensis* with male *M. m. musculus* from Moscow and Moscow region, the breeding intensity was significantly reduced, suggesting the development of postcopulatory mechanisms of isolation between subspecies. A certain degree of asymmetry was identified in the crosses of *M. m. gansuensis* and *M. m. wagneri.*

Interpopulation crosses between remote populations of the same subspecies may also shed light on the development of postcopulatory barriers in geographic isolation. In view of this, we performed several variants of interpopulation crosses (Table 3). Despite the relatively small number of experiments, a certain reduction in the breeding intensity was detected in the crosses of *M. m. musculus* from Moscow and Moscow region and from Chisinau.

As expected, in the backcross of hybrids, high breeding indices were obtained (Table 4). Usually, in backcrosses with the involvement of hybrid females, no decrease in fertility or viability of progeny is observed. Additionally, these indices were much higher than in the crosses involving hybrids males and sometimes the control ones. This is indicated by the data obtained by a number of authors during experimental hybridization of different forms and strains of house mice (Biddle et al., 1994; Britton-Davidian et al., 2005; White et al., 2011). Published data and our results indicate that the hybrid females do not have reduced fertility and viability, which may be observed in males (White et al., 2011). In our experiments, although the hybrid males had a reduced viability, the surviving individuals were fertile. Experimental crosses between different subspecies and populations testify to the initial stages of development of postcopulative reproductive isolation between some forms of house mice.

CONCLUSIONS

According to our data, the degree of development of postcopulative reproductive isolation between the subspecies *M. m. musculus* and *M. m. wagneri* was greater than that between the other forms studied. On the basis of the results of our experiments, the presence of mechanisms that restrict hybridization between different subspecies and geographically remote populations of house mice can be assumed, and the identified asymmetry of crosses may testify to the early stages of divergence between populations and subspecies of *M. musculus*. However, the process of divergence is largely counteracted by the resettlement of different forms of house mice with humans, which causes extensive hybridization of different taxa (Mezhzherin et al., 1994; Kotenkova, 2000; 2002; Spiridonova et al., 2008a, 2011). Undoubtedly, due to the small number of pairs formed, in some variants of crosses our assumptions are probabilistic and require additional verification.

The results obtained in this study, together with the earlier data on the difference of chemical signals in

M. m. wagneri, on the one hand, and *M. m. musculus* and *M. m. gansuensis,* on the other (Maltsev and Kotenkova, 2013), confirm the substantial degree of divergence of the subspecies *M. m. wagneri* from others. Since differences in smells underlie the precopulatory mechanisms of isolation between different species of house mice (Kotenkova et al., 1989; Kotenkova and Naidenko, 1999; Kotenkova and Ambaryan, 2003; Voznesenskaya et al., 2010; Kotenkova, 2014), the identified difference in this case may be the initial stage of development of the precopulatory reproductive isolation between the subspecies. A number of studies performed with the species and populations of the same species of the genus *Drosophila* and other organisms showed that the precopulatory isolation and sterility of hybrids between different forms develop faster than postcopulatory isolation and nonviability of hybrids (Blair, 1964; Prager and Wilson, 1975; Coyne and Orr, 1989, 1998; Gleason and Ritchie, 1998; Mendelson, 2003). The results of studies with house mice are consistent with this assumption. Well-developed precopulatory isolation mechanisms that reliably function in nature were found between the sympatric species of house mice (*M. musculus* and *M. spicilegus*) (Sokolov et al., 1990; Ambaryan et al., 2010). However, the postcopulatory isolation mechanisms are less developed, as is evidenced by the successful crosses of these species in the laboratory, as well as the viability and even fertility of the hybrids obtained in experimental crosses (Lavrenchenko et al., 1994). According to our data, the pre- and postcopulatory mechanisms of isolation between *M. m. wagneri* and *M. m. musculus* at the initial stage are formed synchronously. For example, along with the difference in the odour of urine, restrictions on the crosses of these subspecies have been revealed. Thus, the results of this study suggest that both isolation mechanisms can manifest themselves at the early stages of divergence (subspecies level), so that their effect on the divergence is summed and enhanced. Thus, we have shown the formation of both pre- and postcopulatory mechanisms of isolation between the subspecies *M. m. musculus* and *M. m. wagneri* at the very initial stages.

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REFERENCES

Alibert, P., Fer-Clair, F., Manolakou, K., Britton-Davidian, J., and Auffray, J.-C., Developmental stability, fitness and trait size in laboratory hybrids between European subspecies of the house mouse, *Evolution*, 1997, vol. 51, pp. 284–1295.

Ambaryan, A.V., Maltsev, A.N., and Kotenkova, E.V., Relationship of characteristics of sexual behavior and competitiveness indices of male sperm in taxa of the supraspecies complex *Mus musculus* s. l., *Zh. Obshch. Biol.*, 2015, vol. 76, no. 3, pp. 212–224.

Ambaryan, A.V., Voznesenskaya, V.V., and Kotenkova, E.V., Reproductive isolation in house mice: physiological and ethological mechanisms of precopulatory isolation in house mice of the supraspecies complex *Mus musculus* s. l., Saarbrucken: LAP LAMBERT Academic Publishing GmbH & Co. KG, 2010.

Arnold, S.J., Verrell, P.A., and Tilley, S.G., The evolution of asymmetry in sexual isolation: a model and a test case, *Evolution*, 1996, vol. 50, pp. 1024–1033.

Berry, R.J. and Scriven, P.N., The house mouse: a model and motor for evolutionary understanding, *Biol. J. Linnean Soc.*, 2005, vol. 84, pp. 335–347.

Bhattacharyya, T., Gregorova, S., Mihola, O., Anger, M., Sebestova, J., et al., Mechanistic basis of infertility of mouse intersubspecific hybrids, *Proc. Natl. Acad. Sci.*, 2013, vol. 110, pp. 468–477.

Biddle, F.G., Eales, B.A., and Dean, W.L., Haldane's rule and heterogametic female and male sterility in the mouse, *Genome*, 1994, vol. 37, pp. 198–202.

Blair, W.F., Isolating mechanisms and interspecies interactions in anuran amphibians, *Quart. Rev. Biol.*, 1964, vol. 39, pp. 334–344.

Bonhomme, F., Anand, R., Darviche, D., Din, W., and Boursot, P., The mouse as a ring species?, in *Genetics in Wild Mice. Its Application to Biomedical Research*, Moriwaki, K., Shiroishi, T., and Yonekawa, H., Eds., Tokyo: Japan Scientific Societies Press, 1994, pp. 13–23.

Britton-Davidian, J., Fel-Clair, F., Lopez, J., Alibert, P., and Boursot, P., Postzygotic isolation between the two European subspecies of the house mouse: estimates from fertility patterns in wild and laboratory-bred hybrids, *Biol. J. Linnean Soc.*, 2005, vol. 84, pp. 379–393.

Bulatova, N.Sh., Karyological diversity and relatedness in Asian *Mus,* in *Domovaya mysh'. Proiskhozhdenie, rasprostranenie, sistematika, povedenie* (The House Mouse: Origin, Distribution, Taxonomy, and Behavior), Kotenkova, E.V. and Bulatova, N.Sh., Eds., Moscow: Nauka, 1994, pp. 154–172.

Bulatova, N.Sh., Kotenkova, E.V., and Lyalyukhina, S.I., Fertility of hybrids and the cytogenetic effect of hybrid dysgenesis in the crosses of mound-building, house, and laboratory mice, *Dokl. Akad. Nauk SSSR*, 1986, vol. 288, no. 4, pp. 1018–1020.

Capanna, E., Gropp, A., and Winking, H., Robertsonian metacentrics in the mouse, *Chromosoma*, 1976, vol. 58, pp. 341–353.

Coyne, J.A. and Orr, H.A., Patterns of speciation in *Drosophila, Evolution*, 1989, vol. 43, pp. 362–381.

Coyne, J.A. and Orr, H.A., The evolutionary genetics of speciation, *Phil. Transact. Roy. Soc. Lond. Ser. B*, 1998, vol. 353, pp. 287–305.

Coyne, J.A. and Orr, H.A., *Speciation*, Sunderland: Sinauer Associates Inc., 2004.

Elliott, R.W., Miller, D.R., Pearsall, R.S., Hohman, C., Zhang, Y., et al., Genetic analysis of testis weight and fertility in an interspecies hybrid congenic strain for chromosome X, *Mamm. Genome*, 2001, vol. 12, pp. 45–51.

Forejt, J., Piálek, J., and Trachtulec, Z., Hybrid male sterility genes in the mouse subspecific crosses, in *Evolution of the House Mouse, Cambridge Series in Morphology and Molecules: New Paradigms in Evolutionary Biology,* Macholan, M., Baird, S.J., Muclinger, P., and Pialek, P., Eds., Cambridge: Cambridge Univ. Press, 2012, pp. 482–503.

Forejt, J. and Ivanyi, P., Genetic studies on male sterility of hybrids between laboratory and wild mice (*Mus musculus* L.), *Genet. Res.,* 1974, vol. 24, pp. 189–206.

Forejt, J., Hybrid sterility in the mouse, *Trends Genet.*, 1996, vol. 12, pp. 412–417.

Gleason, J.M. and Ritchie, M.G., Evolution of courtship song and reproductive isolation in the *Drosophila willistoni* species complex: do sexual signals diverge the most quickly?, *Evolution*, 1998, vol. 52, pp. 1493–1500.

Good, J.M., Handel, M.A., and Nachman, M.W., Asymmetry and polymorphism of hybrid male sterility during the early stages of speciation in house mice, *Evolution*, 2008, vol. 62, pp. 50–65.

Haldane, J.B.S., Sex ratio and unisexual sterility in hybrid animals, *J. Genet.*, 1922, vol. 12, pp. 101–109.

Kaneshiro, K.Y., Sexual isolation, speciation, and the direction of evolution, *Evolution*, 1980, vol. 34, pp. 437–444.

Korobitsyna, K.V. and Yakimenko, L.V., The role and place of *wagneri*-like forms of house mouse (Rodentia, Muridae) in the fauna of Russia and adjacent countries, *Zool. Zh.*, 2004, vol. 83, no. 8, pp. 1018–1030.

Kotenkova, E.V., Synanthropic and wild mice of the supraspecies complex *Mus musculus* s. l.: systematics, distribution, lifestyle, isolation mechanisms, and evolution, *Extended Abstract of Doctoral (Biol.) Dissertation*, Moscow: Severtsov Inst. Ecol. Evol., 2000.

Kotenkova, E.V., Hybridization of commensal species of house mice and its role in evolution, *Usp. Sovrem. Biol.*, 2002, vol. 122, no. 6, pp. 580–593.

Kotenkova, E.V., Comparative analysis of ethological and physiological mechanisms of precopulatory reproductive isolation in rodents, *Usp. Sovrem. Biol.*, 2014, vol. 134, no. 5, pp. 488–518.

Kotenkova, E.V. and Ambaryan, A.V., Ethological mechanisms of reproductive isolation in house mice of the supraspecies complex *Mus musculus* s. l., *Usp. Sovrem. Biol.*, 2003, vol. 123, no. 6, pp. 599–608.

Kotenkova, E.V. and Naidenko, S.V., Discrimination of con- and heterospecific odors in different taxa of the *Mus musculus* species group: olfactory cues as precopulatory isolating mechanism, in *Advances in Chemical Communication in Vertebrates*, Johnston, R.E., Muller-Schwarze, D., and Sorensen, P., Eds., New York: Plenum Press, 1999, pp. 299–308.

Kotenkova, E.V. and Osadchuk, L.V., Effect of odor of commensal house mice on the reproduction of the pine vole *Microtus rossiaemeridionalis, Dokl. Biol. Sci.,* 2009, vol. 426, no. 2, pp. 236–238.

Kotenkova, E.V., Osadchuck, A.V., and Lyalyukhina, S.I., Precopulatory isolating mechanisms between the house and mound-building mouse, *Acta Theriologica*, 1989, vol. 34, pp. 315–324.

Kotenkova, E.V., Meshkova, N.N., and Zagoruiko, N.V., Exploratory behaviour in synanthropic and outdoor mice of superspecies complex *Mus musculus, Polish Ecol. Stud.*, 1994, vol. 20, pp. 377–383.

Kotenkova, E.V., Ambarian, A.V., Kandaurov, A.S., and Meshkova, N.N., Exploratory behavior and response to olfactory cues by the *Mus musculus* species group: implications for the origins of Transcaucasian forms of *Mus*, in *Rats, Mice and People: Rodent Biology and Management*, Singleton, G.R., Hinds, L.A., Krebs, C.J., and Spratt, D.M., Eds., ACIAR Monographs, 2003, pp. 151–154.

Kovalskaya, Yu.M., Savinetskaya, L.E., and Aksenova, T.G., Experimental hybridization of voles of the genus *Microtus* s. l. *M. socialis* with species of the group *arvalis* (Mammalia, Rodentia), *Biol. Bull.* (Moscow), 2014, vol. 41, no. 6, pp. 559–564.

Lavrenchenko, L.A., Kotenkova, E.V., Bulatova, N.Sh., and Lyalyukhina, S.I., Hybridological analysis of forms of the supraspecies complex *Mus musculus* s. lato, in *Domovaya mysh'* (The House Mouse), Sokolov, V.E., Kotenkova, E.V., Krasnov, B.R., and Meshkova, N.N., Eds., Moscow: IEMEZh AN SSSR, 1989, pp. 135–143.

Lavrenchenko, L.A., Kotenkova, E.V., and Bulatova, N.Sh., Experimental hybridization of house mice, in *Domovaya mysh'. Proiskhozhdenie, rasprostranenie, sistematika, povedenie* (The House Mouse: Origin, Distribution, Taxonomy, and Behavior), Kotenkova, E.V. and Bulatova, N.Sh., Eds., Moscow: Nauka, 1994, pp. 93–109.

Lavrenchenko, L.A., Systematic analysis of the supraspecies complex *Mus musculus* s. lato, *Extended Abstract of Cand. Sci. (Biol.) Dissertation*, Moscow: Severtsov Inst. Ecol. Evol., 1990.

Linnaeus, C., *Systema Naturae per Regna Tria Naturae, Secundum Classes, Ordines, Genera, Species, Cum Characteribus, Differentii, Synonymis, Locies,* 10th ed., Stockholm: Laurentius Salvius, 1758, vol. 1.

Maltsev, A.N., Taxonomic evaluation of populations of house mice of Ishim on the basis of phenotypic characteristics, in Divertisitatea, valorificarea raţională şi protectia lumii animale: Simpoz. Intern. Ch.: I.E. Stiinta, 2009, pp. 63–65.

Maltsev, A.N., Microevolution and intraspecific structure of the house mouse *Mus musculus, Extended Abstract of Cand. Sci. (Biol.) Dissertation*, Moscow: Severtsov Inst. Ecol. Evol., 2011a.

Maltsev, A.N., Molecular genetic variability of subspecies of house mice *Mus musculus* according to the study of polymorphism of mtDNA control region, in *Intellektual'nyi potentsial XXI veka: stupeni poznaniya: Sbornik materialov VII Mezhdunarodnoi studencheskoi nauchno-prakticheskoi konferentsii* (The Intellectual Potential of the XXI Century: The Levels of Cognition. Proceedings of the VII International Student Scientific and Practical Conference), Chernov, S.S., Eds., Novosibirsk: Izd. NGTU, 2011b, pp. 12–18.

Maltsev, A.N. and Bazhenov, Yu.A., Phylogeography of the house mouse *Mus musculus* on the territory of Russia and Adjacent Countries and the role of invasions, *Zhiv. Biocos. Sist.* [electronic resource], 2013, no. 5. http://www.jbks.ru/archive/issue-5/article-11.

Maltsev, A.N. and Kotenkova, E.V., The divergence of olfactory signals in the house mouse subspecies *Mus musculus, Usp. Sovrem. Biol.*, 2013, vol. 133, no. 2, pp. 152–163.

Malygin, V.M., *Sistematika obyknovennykh polevok* (Systematics of Common Voles), Moscow: Nauka, 1983.

Marshall, J.T., *Identification and Scientific Names of Eurasian House Mice and Their European Allies, Subgenus Mus (Rodentia: Muridae),* Virginia: Museum National History, 1998.

Meier, M.N., Grishchenko, G.A., and Zybina, E.V., Experimental hybridization as a method to study the degree of divergence of closely related species of voles of the genus *Microtus, Zool. Zh.*, 1981, vol. 60, no. 2, pp. 290–300.

Meier, M.N., Golenishchev, F.N., Radzhabli, S.I., and Sablina, O.V., *Serye polevki (podrod Microtus) fauny Rossii i sopredel'nykh territorii* (Common voles (subgenus *Microtus*) of Russia and Adjacent Countries), *Trudy Zool. Inst. RAN*, 1996, vol. 232.

Mendelson, T.C., Sexual isolation evolves faster than hybrid inviability in a diverse and sexually dimorphic genus of fish

(Percidae: Etheostoma), *Evolution*, 2003, vol. 57, pp. 317–327.

Mezhzherin, S.V., Taxonomy and modern views on the system of house mice of the Palaearctic, in *Domovaya mysh'. Proiskhozhdenie, rasprostranenie, sistematika, povedenie* (The House Mouse: Origin, Distribution, Taxonomy, and Behavior), Kotenkova, E.V. and Bulatova, N.Sh., Eds., Moscow: Nauka, 1994, pp. 15–36.

Mezhzherin, S.V. and Kotenkova, E.V., Genetic marking of subspecies of house mice of the fauna of the USSR, *Dokl. Akad. Nauk SSSR*, 1989, vol. 304, no. 5, pp. 1272–1275.

Mezhzherin, S.V. and Kotenkova, E.V., Biochemical systematics of the house mice in Central Palearctic region, *Zeitschrift für zoologische Systematik und Evolutionsforschung*, 1992, vol. 30, pp. 180–188.

Mezhzherin, S.V., Kotenkova, E.V., and Mikhailenko, A.G., Hybrid zones, in *Domovaya mysh'. Proiskhozhdenie, rasprostranenie, sistematika, povedenie* (The House Mouse: Origin, Distribution, Taxonomy, and Behavior), Kotenkova, E.V. and Bulatova, N.Sh., Eds., Moscow: Nauka, 1994, pp. 37–50.

Milishnikov, A.N., Comparative protein variability in populations, in *Domovaya mysh'. Proiskhozhdenie, rasprostranenie, sistematika, povedenie* (The House Mouse: Origin, Distribution, Taxonomy, and Behavior), Kotenkova, E.V. and Bulatova, N.Sh., Eds., Moscow: Nauka, 1994, pp. 116–153.

Moriwaki, K., Miyashita, N., Suzuki, H., Kurihara, Y., and Yonekawa, H., Genetic features of major geographical isolates of *Mus musculus*, in *Current Topics in Microbiology and Immunology*, Potter, M., Nadeau, J.H., and Cancro, M.P., Eds., 1986, vol. 127, pp. 55–61.

Prager, E.R. and Wilson, A.C., Slow evolutionary loss of the potential for interspecific hybridization in birds: a manifestation of slow regulatory evolution, *Proc. Natl. Acad. Sci.,* 1975, vol. 72, pp. 200–204.

Rutty, J., *An Essay Towards the Natural History of the Country of Dublin*, Dublin: Sleater, 1772, vol. 1.

Sage, R.D., Atchley, W.R., and Capanna, E., House mice as models in systematic biology, *Syst. Biol.*, 1993, vol. 42, pp. 523–561.

Sludskii, A.A., Bekenov, A., Borisenko, V.A., Grachev, Yu.A., Ismagilov, M.I., et al., *Mlekopitayushchie Kazakhstana* (Mammals of Kazakhstan), Alma-Ata: Nauka Kazakhskoi SSR, 1977, vol. 1, Part 2.

Sokolov, V.E., Kotenkova, E.V., and Lyalyukhina, S.I., *Biologiya domovoi i kurganchikovoi myshei* (Biology of House and Mound-Building Mice), Moscow: Nauka, 1990.

Sokolov, V.E., Zagoruiko, V.N., Meshkova, N.N., and Kotenkova, E.V., Exploratory behavior of synantropic and outdoor forms of house mice of superspecies *Mus musculus* s. lato: a comparative analysis, *Dokl. Akad. Nauk*, 1993, vol. 332, no. 4, pp. 541–543.

Spiridonova, L.N., Kisilev, K.V., and Korobitsyna, K.V., Discordance in the distribution of markers of different inheritance systems (nDNA, mtDNA, and chromosomes) in the superspecies complex *Mus musculus* as a result of extensive hybridization in Primorye, *Russ. J. Genet.*, 2011, vol. 47, no. 1, pp. 100–109.

Spiridonova, L.N., Korobitsyna, K.V., Yakimenko, L.V., and Bogdanov, A.S., Genetic diversity of the house mouse *Mus musculus* and geographic distribution of its subspecies-specific RAPD markers on the territory of Russia, *Russ. J. Genet.*, 2008a, vol. 44, no. 5, pp. 584–594.

Spiridonova, L.N., Korobitsyna K V., Yakimenko, L.V., and Bogdanov, A.S., Genetic differentiation of subspecies of the house mouse *Mus musculus* and their taxonomic relationships inferred from RAPD-PCR data, *Russ. J. Genet.*, 2008b, vol. 44, no. 6, pp. 732–739.

Tsuchiya, K., Miyashita, N., Wang, C.H., Wu, X.-L., He, X.-Q., et al., Taxonomic study of the genus *Mus* in China, Korea and Japan, in *Genetics in Wild Mice*, Tokyo: Japan Science Society Press, 1994, pp. 3–12.

Tucker, K., Evolutionary history of the genus *Mus*, in *Eye, Retina, and Visual System of the Mouse*, Chalupa L.M. and Williams, R.W., Eds., MIT Press, 2008, pp. 3–12.

Tupikova, N.V., Ecology of the house mouse in the middle belt of the USSR, *Fauna Ekol. Gryzunov*, 1947, no. 2, pp. 5–67.

Turelli, M. and Orr, H.A., The dominance theory of Haldane's rule, *Genetics*, 1995, vol. 140, pp. 389–402.

Turelli, M., Barton, N., and Coyne, J., Theory and speciation, *Trends Ecol. Evol.*, 2001, vol. 16, pp. 330–343.

Turner, L.M., Schwahn, D.J., and Harr, B., Reduced male fertility is common but highly variable in form and severity in a natural house mouse hybrid zone, *Evolution*, 2012, vol. 66, pp. 443–458.

Vinogradov, B.S., Argiropulo, A.I., and Geptner, V.G., *Gryzuny Srednei Azii* (Rodents of Central Asia), Moscow: Izd. Akad. Nauk SSSR, 1936.

Voznesenskaya, A.E., Ambaryan, A.V., Klyuchnikova, M.A., Kotenkova, E.V., and Voznesenskaya, V.V., Mechanisms of reproductive isolation in house mouse superspecies complex *Mus musculus* s. lato: from behaviour to receptors, *Dokl. Biol. Sci.*, 2010, vol. 435, pp. 418–420.

Watanabe, T.K. and Kawanishi, M., Mating preference and the direction of evolution in *Drosophila, Science*, 1979, vol. 205, no. 4409, pp. 906–907.

Waterhouse, G.S., Description of two new species of the genus *Mus, Proc. Zool. Soc. Lond.*, 1842, vol. 10, pp. 145–146.

White, M.A., Steffy, B., Wiltshire, T., and Payseur, B.A., Genetic dissection of a key reproductive barrier between nascent species of house mice, *Mus musculus domesticus* and *Mus musculus musculus, Genetics*, 2011, vol. 169, pp. 289–304.

Wu, C.-I., The genic view of the process of speciation, *J. Evol. Biol.,* 2001, vol. 14, pp. 851–865.

Yakimenko, L.V., Korobitsyna, K.V., Frisman, L.V., Morivaki, K., and Ionekava, Kh., Genetic studies on house mice from the hybrid zone of Primorskii Krai, *Russ. J. Genet.*, 2000, vol. 36, no. 1, pp. 66–75.

Yakimenko, L.V., Korobitsyna, K.V., Frisman, L.V., Morivaki, K., and Ionekava, Kh., Cytogenetics and taxonomy of house mice in Russia and adjacent countries, in *Problemy evolyutsii. Sbornik nauchnykh trudov* (Problems of Evolution. Collection of Scientific Papers), Vladivostok: Dal'nauka, 2003, vol. 5, pp. 62–89.

Yonekawa, H., Tsuda, K., Tsuchiya, K., Yakimenko, L.V., Korobitsyna, K.V., et al., Genetic diversity, geographic distribution, and evolutionary relationships of *Mus musculus* subspecies based on polymorphisms of mitochondrial DNA, in *Problemy evolyutsii. Sbornik nauchnykh trudov* (Problems of Evolution. Collection of Scientific Papers), Vladivostok: Dal'nauka, 2003, vol. 5, pp. 90–108.

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